The first steps in the life of a short GRB

Miguel Angel Aloy Toras

Max-Planck-Institut
für Astrophysik

A collaboration with

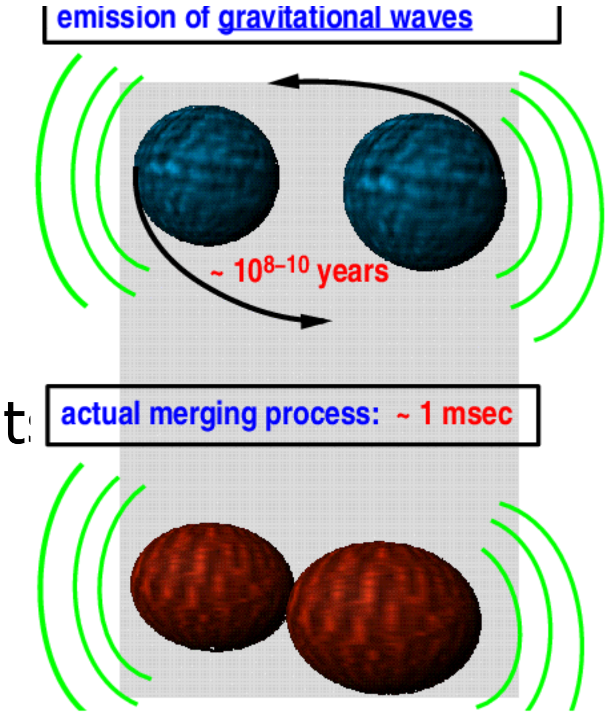
E. Müller & H.-T. Janka

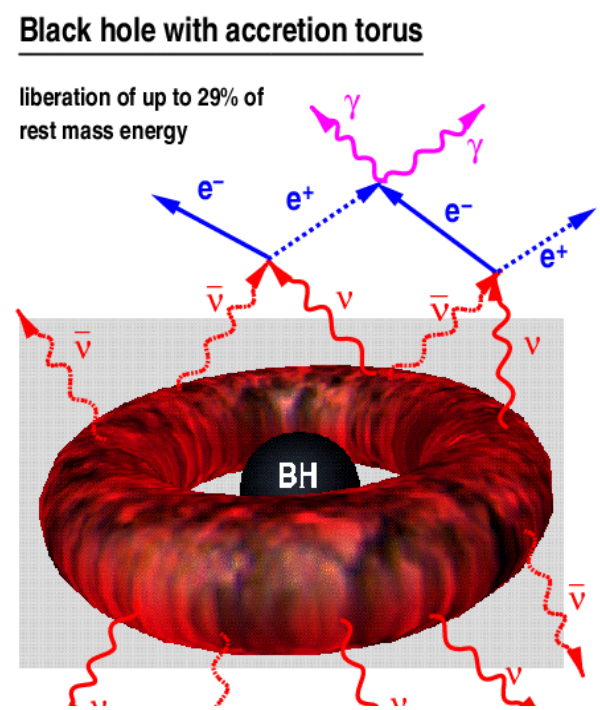
GRBs, progenitors:

- More than 200 competing models
- Difficult to identify because of lack of observational accuracy
- Most promising: catastrophic collapse events
  1) Death of massive stars
     a) Collapsars (Woosley)
     b) Hypernovae (Pacynski)
     ⇒ Sources of long GRBs
  2) Mergers of compact binaries
     (Pacynski, Goodman, Eichler et al., Mochkovitch et al.)
     ⇒ Sources of short GRBs & strong GWs

Common scenario:

A stellar mass black hole accretes several M_{sol} of matter and produces a relativistic pair fireball

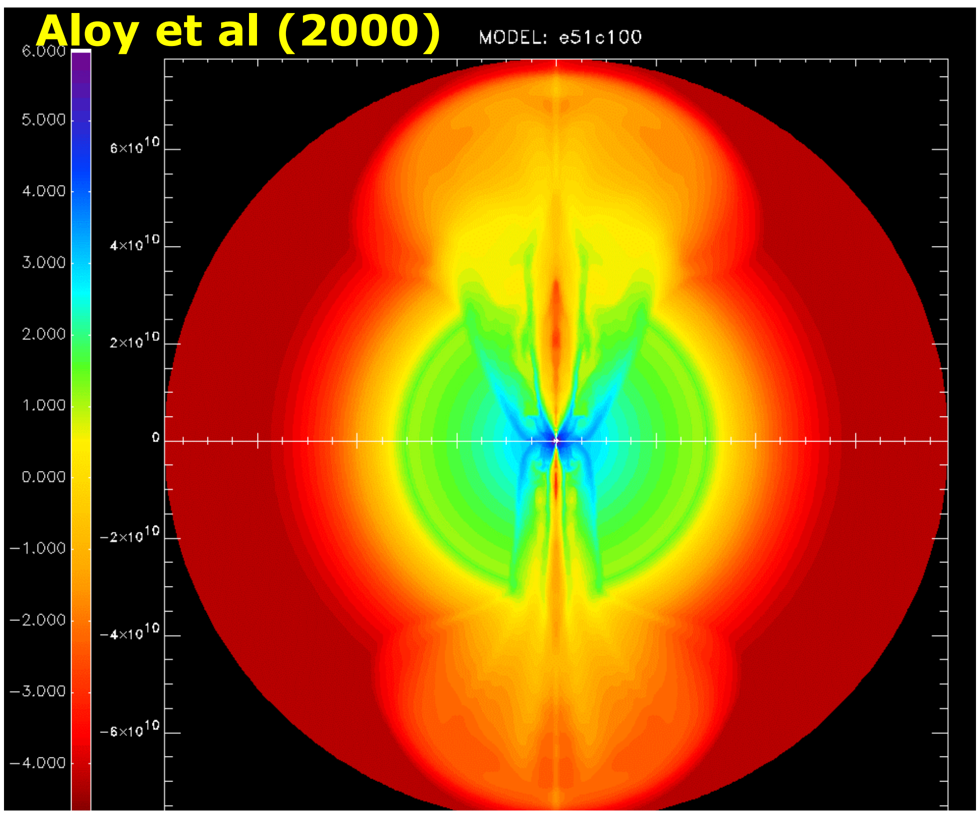


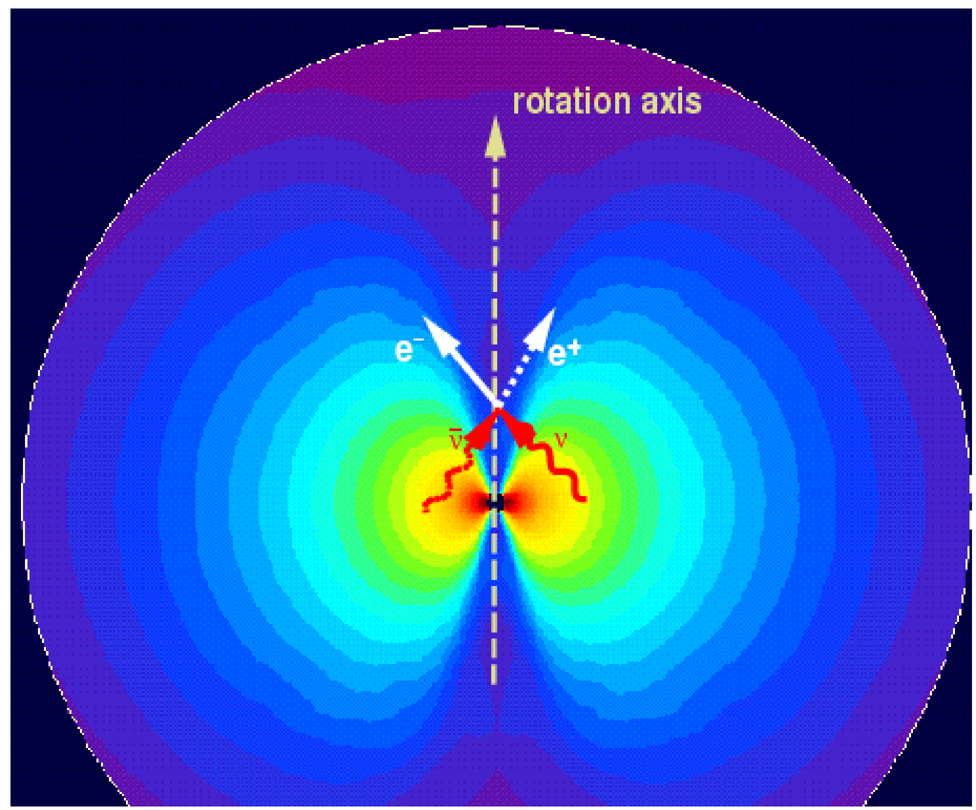


GRBs, progenitors: long bursts

Collapsars (Woosley 1993)

- Collapse of a massive (WR) rotating star that does not form a successful SN to a BH ($M_{BH} \sim 3M_{sol}$) surrounded by a thick accretion disk. The hydrogen envelope is lost by stellar winds, interaction with a companion, etc.
- The viscous accretion onto the BH ⇒ strong heating ⇒ thermal $\nu\tilde{\nu}$ annihilating preferentially around the axis ⇒ fomation of a relativistic jet (□>10).

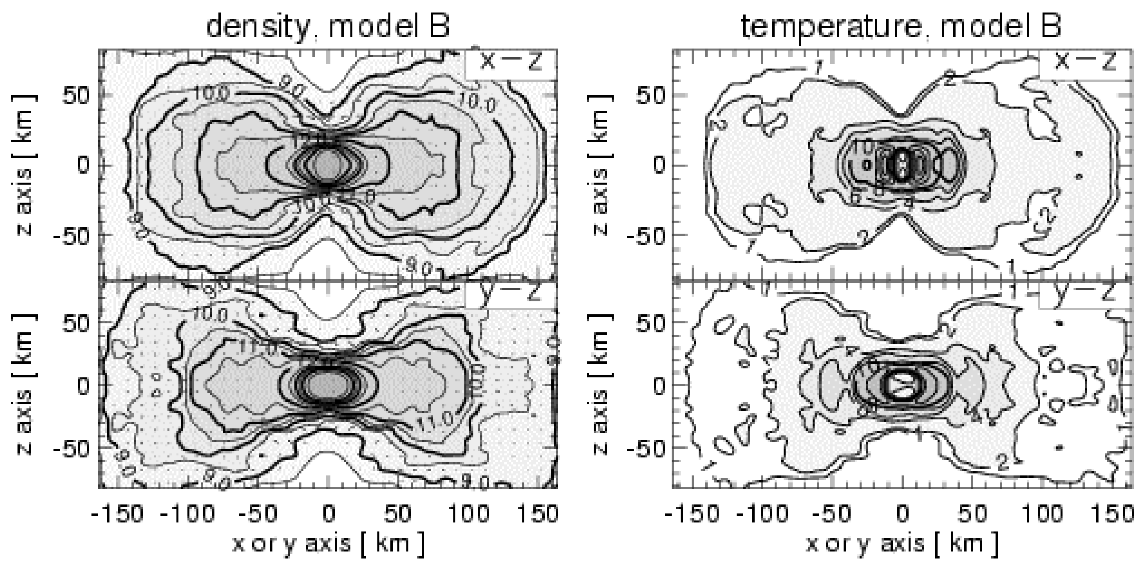




GRBs, progenitors: short bursts?

Merger of a system of compact binaries (SCBs):

- After the merger of a SCB a central BH (M_{BH} ~ 2-3M_{sol}) girded by a thick accretion torus (M_{torus}~ 0.05 – 0.3M_{sol}).
- Once the thick disk is formed, up to ~10^{51} ergs can be released above the poles of the BH in a region that contains <10^{-5} M_{sun} of baryonic matter due to $\nu\tilde{\nu}$ annihilations preferentially near axis ⇒ acceleration to ultrarelativistic speeds.
- If the observed duration T_{obs} is related to the lifetime of the system T_a this kind of events can only belong to the class of short GRBs because T_{disk}~ 0.05 – 0.5 s.



The first steps in the life of a short GRB

Our goals:

1. The viability of the scenario of merging SCBs for producing ultrarelativistic outflows (winds, jets, radial outflows?).
2. Mechanism of *collimation* (if any) of the outflowing plasma.
3. Expected durations of the GRB events generated in this framework and their relation to the time during which the source of energy is active (T_a).

How to: GRHD simulations

-Build up a *likely* initial model

Schwarzschild BH

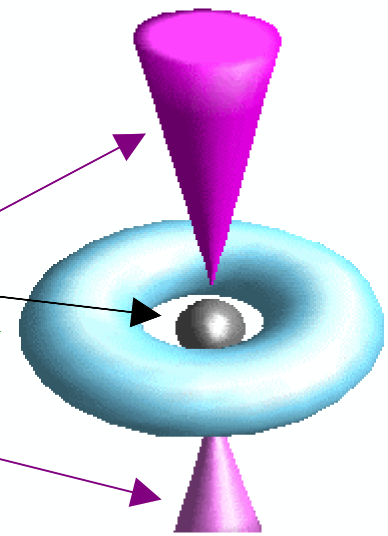
+

thick accretion torus

-Release energy in a baryon clean environment

-EoS: ideal gas of neutrons + e^+e^- + radiation

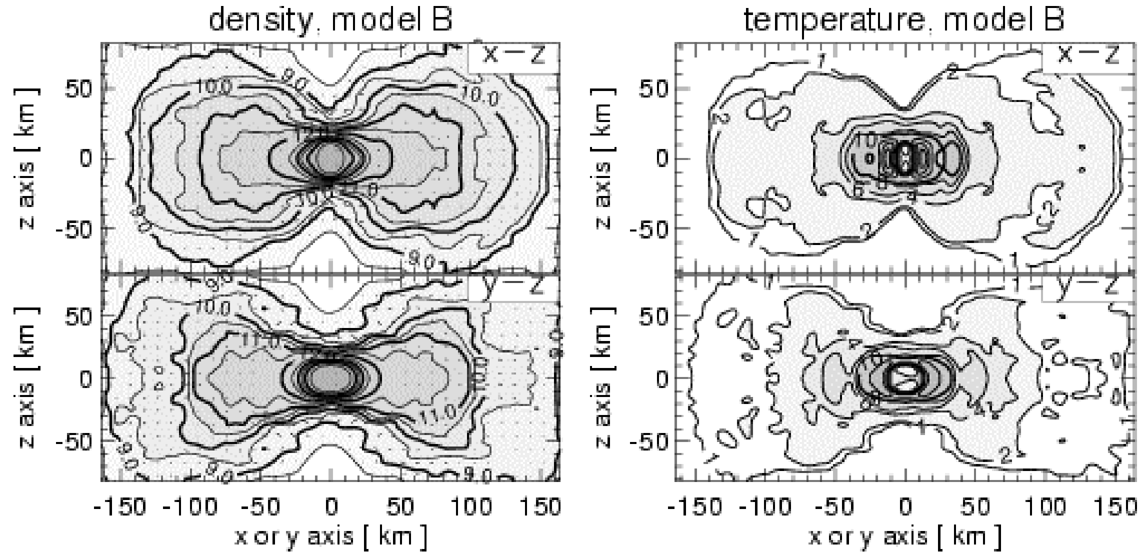
(Witti, Janka & Takahashi 1994)



Initial model

Two approaches:

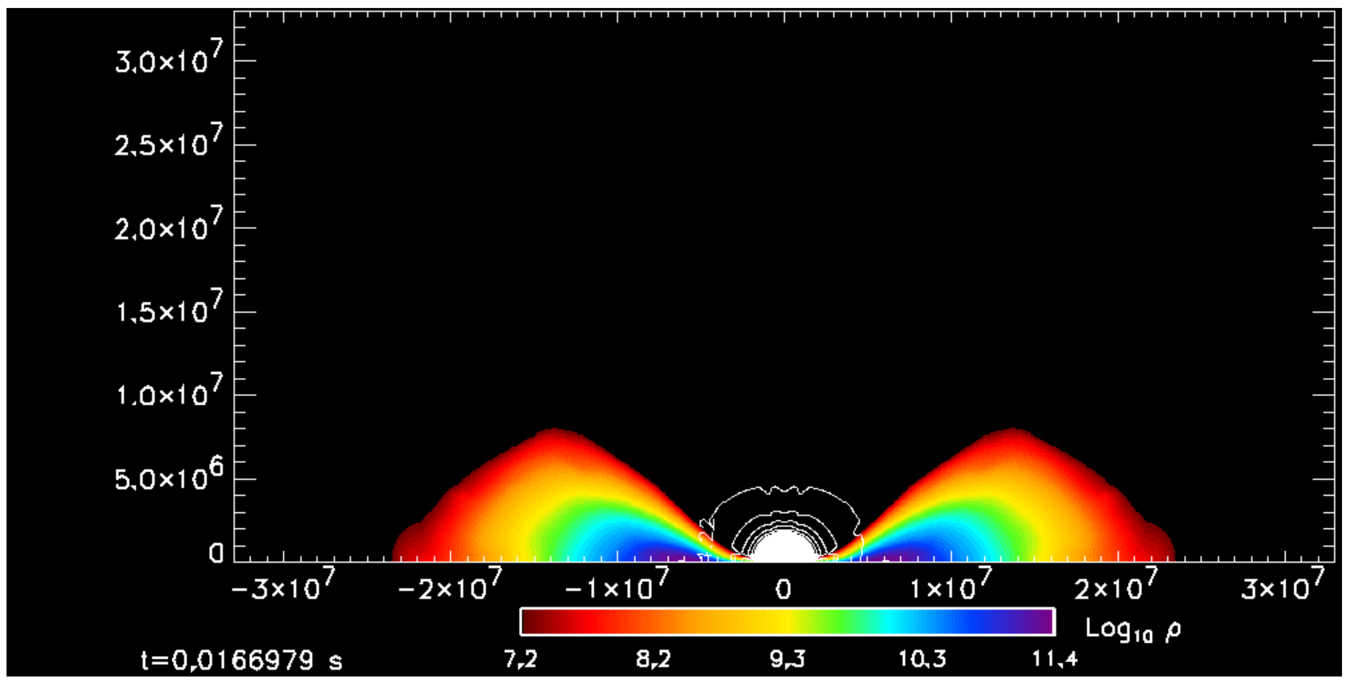
Type-A: Put a toroidal-like distribution of matter and angular momentum around a Schwarzschild BH (guided by the Newtonian simulations of Ruffert & Janka 2001) and let it relax to an equilibrium configuration.



Ruffert & Janka (2001), A&A, 380, 544

$M_{torus} \sim 0.17\ M_{sun}$
$M_{BH} \sim 3\ M_{sun}$
$M_{env} \sim 10^{-2}\ M_{sun}$

Relaxed initial model

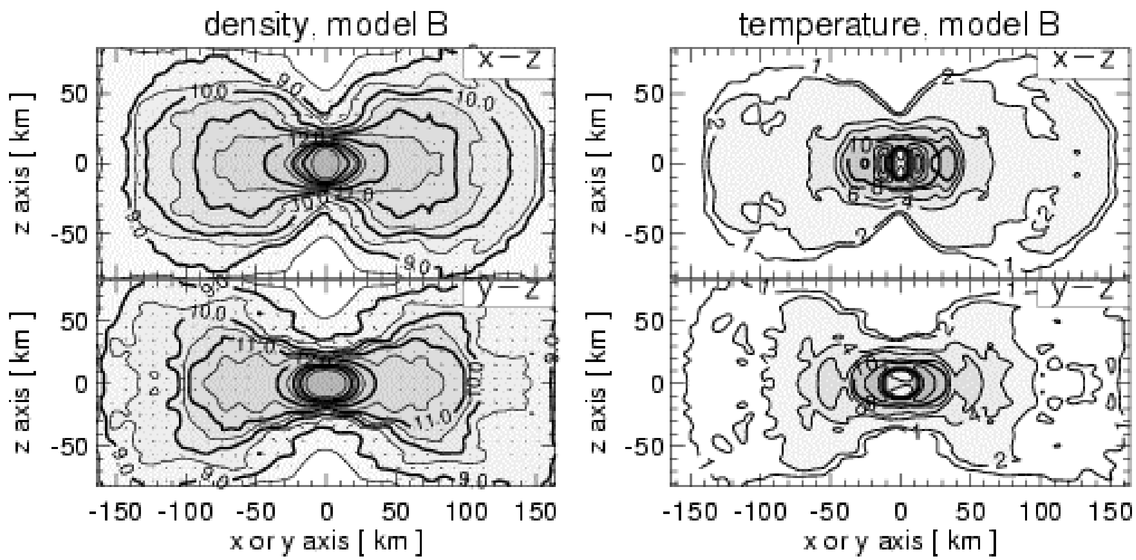


Initial model

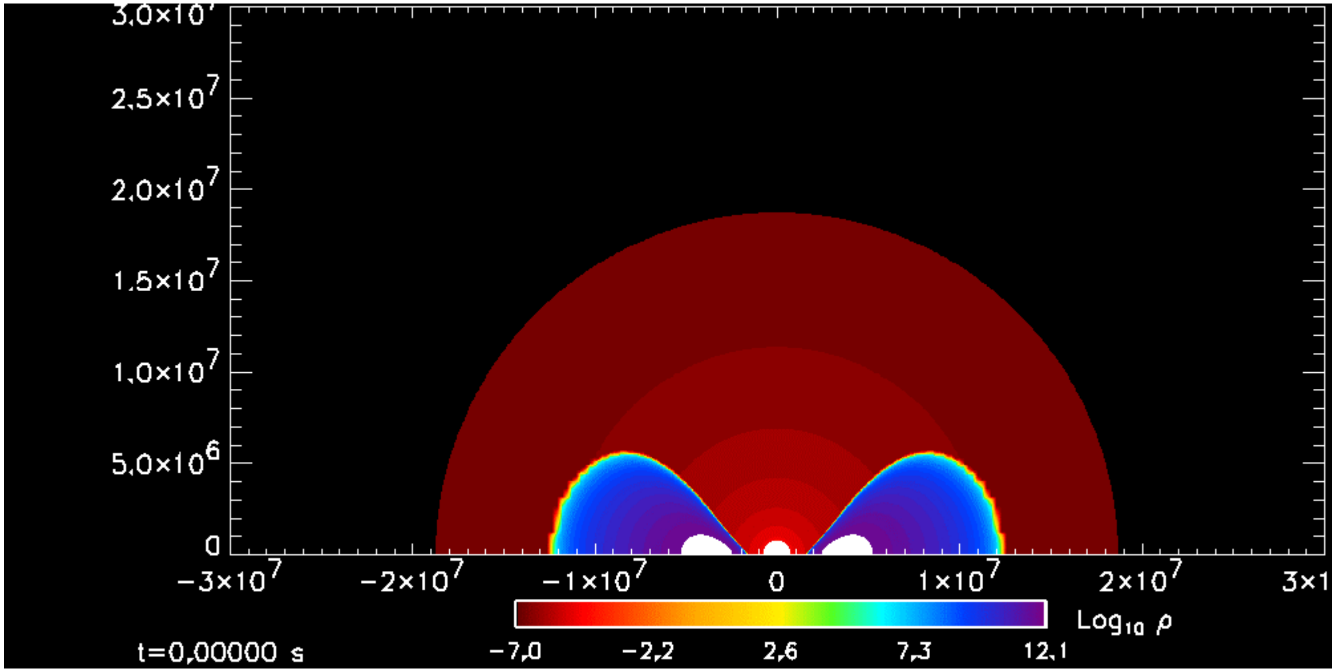
Two approaches:

Type-B: Follow Font & Daigne (2003) prescription to build up equilibrium tori around a BH. Outside use Michel (1972) spherical accretion solution.

$M_{torus} \sim 0.17\ M_{sun}$
$M_{BH} \sim 2.44\ M_{sun}$
$M_{env} \sim 10^{-7}\ M_{sun}$



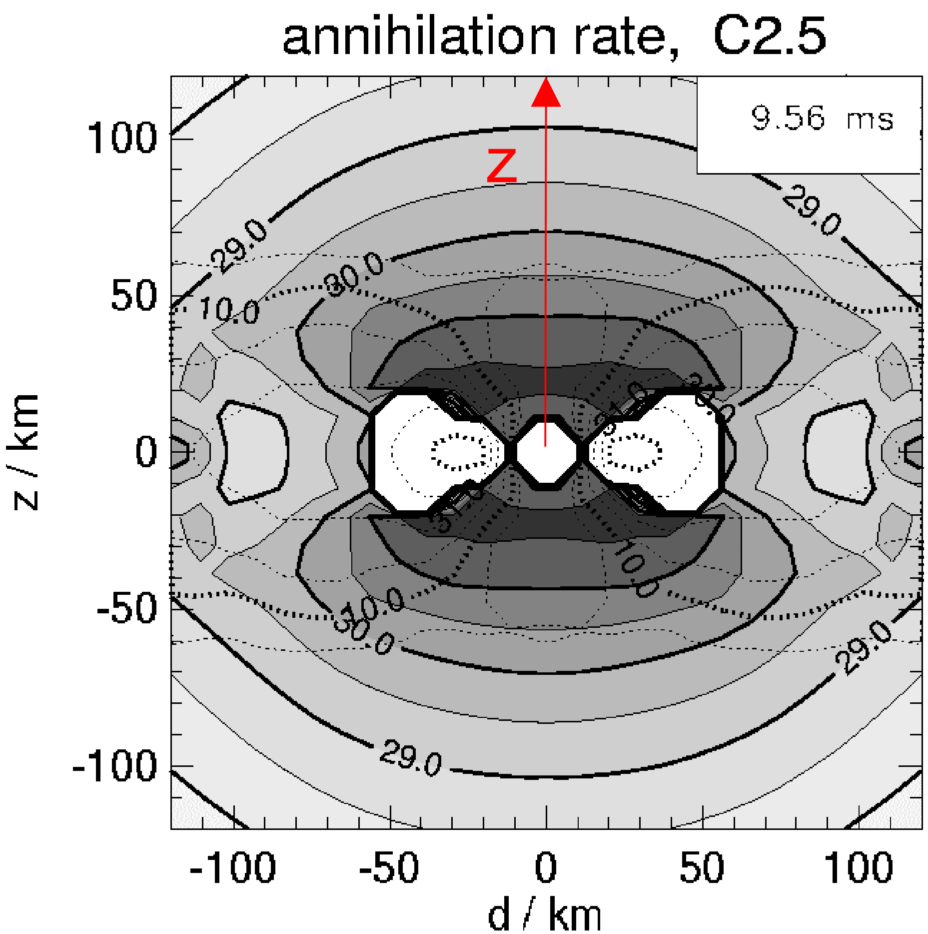
Ruffert & Janka (2001), A&A, 380, 544



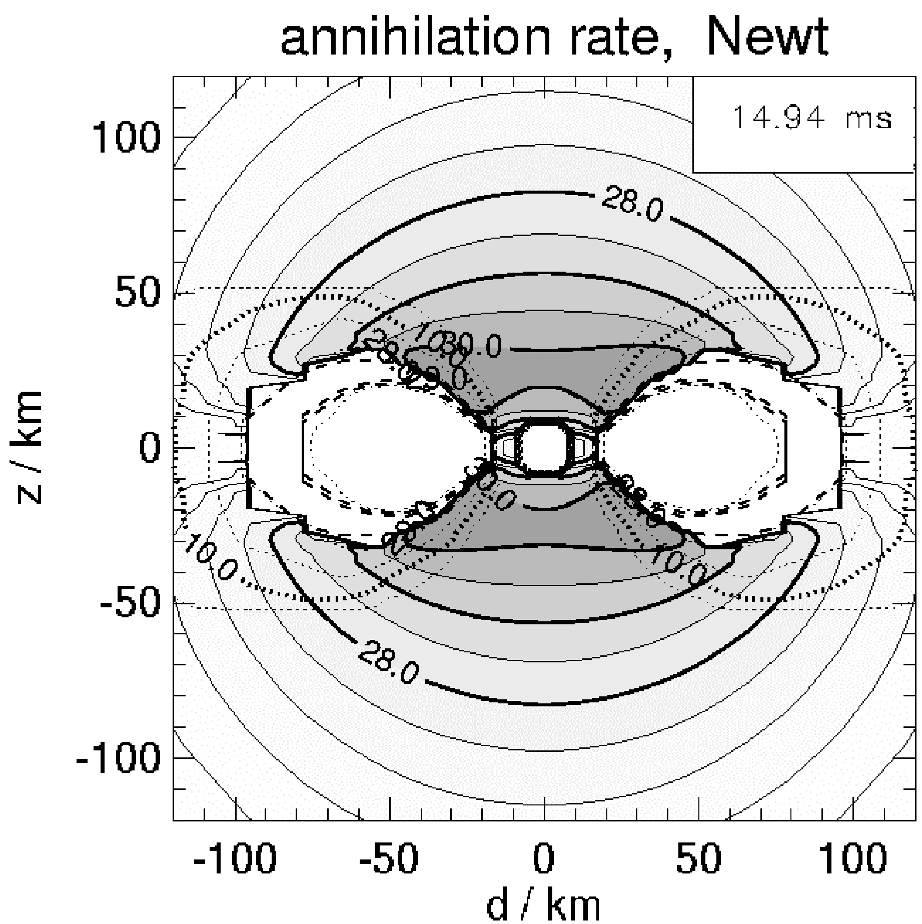
Modeling the energy release

Guided by previous results of Janka, Ruffert et al. showing that both in NS-NS mergers (Ruffert & Janka 1999) and in BH-NS mergers (Janka et al. 1999), can be released up to 10^{51} ergs above the poles of the black hole in a region that contains less than 10^{-5} M_{sun} of baryonic matter. The dependence in z-distance is:

$$q(z) = q_0 / z^n; \quad z = r \sin\theta; \quad n \sim 5; \quad \theta_0 \sim [30^o, 75^o]$$



Janka et al. (1999), ApJ, 527, L39



Ruffert & Janka (1999), A&A, 344, 573

Models explored up to now

- Energy deposition region:

  Cone of 30° to 75° around the rotation axis that extends from R_{min}= 1.02 - 2.05 R_s (innermost boundary) to infinity

- Grids: r (log spaced) x □ (uniform)

  Type A: 460 x 200 zones. R_{max} = 3 x 10^9 cm

  Type B: 500 x 200 zones. R_{max} = 2 x 10^{10} cm

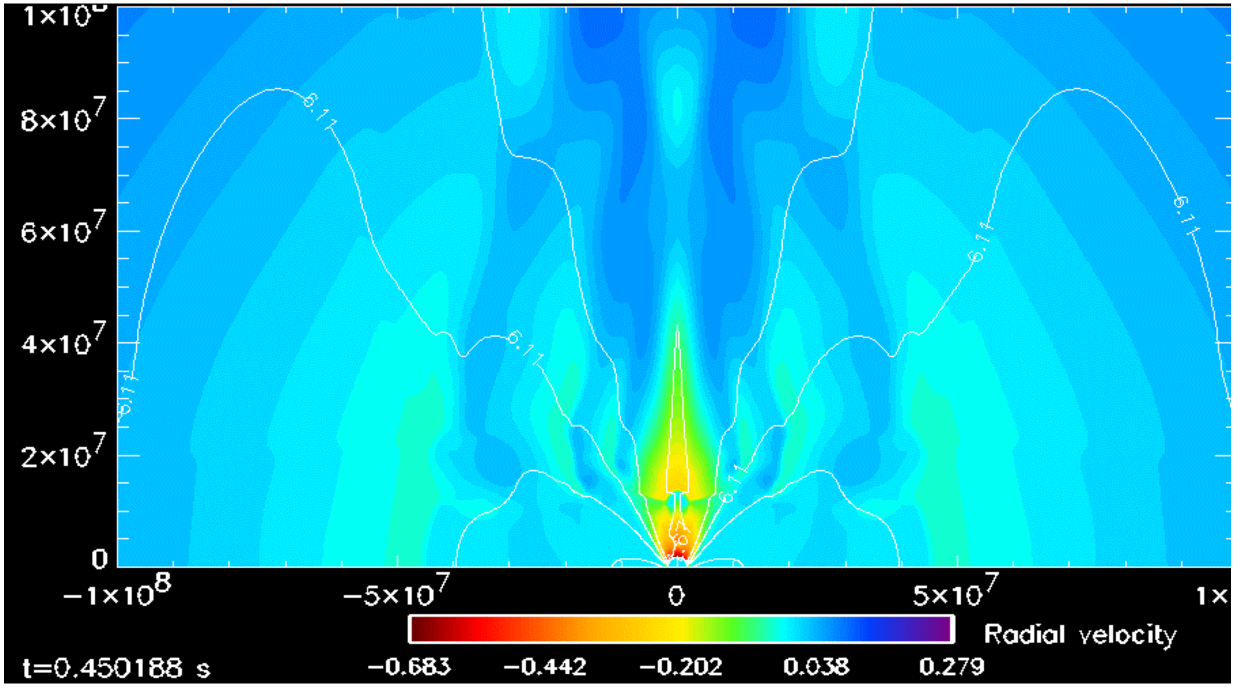
Model	$\dot{E}$	θ_0	$v_p[c]$	Γ_{max}	θ_w	M_f [gr]
A01	10^{49}	$30°$	$(0.67)0.62$	$(17.67)17.87$	$(<1°)<1°$	$3.6 \cdot 10^{25}$
A02	$2 \cdot 10^{50}$	$30°$	$(0.63)0.63$	$(81.10)231.81$	$(11.3°)6°$	$2.2 \cdot 10^{27}$
A03	$2 \cdot 10^{50}$	$45°$	$(0.80)0.67$	$(10.89)26.71$	$(9.5°)2.9°$	$2.4 \cdot 10^{27}$
A04	$2 \cdot 10^{50}$	$75°$	$(0.67)-$	$(6.97)-$	$(8.5°)-$	-
A05	10^{51}	$30°$	$(0.99)0.82$	$(84.00)562.25$	$(15.0°)15°$	$9.7 \cdot 10^{27}$
A06	10^{51}	$45°$	$(0.97)-$	$(79.61)-$	$(15.8°)-$	-
A07	10^{51}	$75°$	$(0.90)0.60$	$(12.97)37.36$	$(12.5°)8.13°$	$7.4 \cdot 10^{27}$
A08	10^{50}	$31.4°$	$(0.83)0.70$	$(19.80)19.99$	$(3.8°)2.9°$	$3.0 \cdot 10^{26}$
A09	$5 \cdot 10^{51}$	$30°$	$(0.70)0.97$	$(90.74)748.06$	$(23°)26°$	$4.0 \cdot 10^{28}$
B01	$2 \cdot 10^{50}$	$45°$	$(0.97)0.999999$	$(27.49)509.03$	$(24°)22°$	$3.1 \cdot 10^{26}$
B02	$2 \cdot 10^{50}$	$60°$	$(0.999)0.999996$	$(52.32)420.57$	$(24°)19°$	$2.2 \cdot 10^{27}$
B03	$2 \cdot 10^{50}$	$75°$	$(0.999)0.99990$	$(129.57)493.03$	$(25°)19°$	$2.6 \cdot 10^{28}$
B04	10^{49}	$45°$	$(0.95)0.99988$	$(42.56)333.58$	$(26°)20°$	$2.4 \cdot 10^{25}$
B05	10^{51}	$45°$	$(0.99)0.999997$	$(70.68)632.26$	$(33°)27°$	$1.3 \cdot 10^{27}$

Results

- $P_{thr} \sim 10^{48\text{-}49}$ erg/s:
  * in the initial model matter falls in through the axis of rotation (v_{in}~0.6c- 0.97c)

  * model dependent but the feature may be generic

  * our threshold is probably higher than in real mergers (type-A) or maybe irrelevant in type-B models.



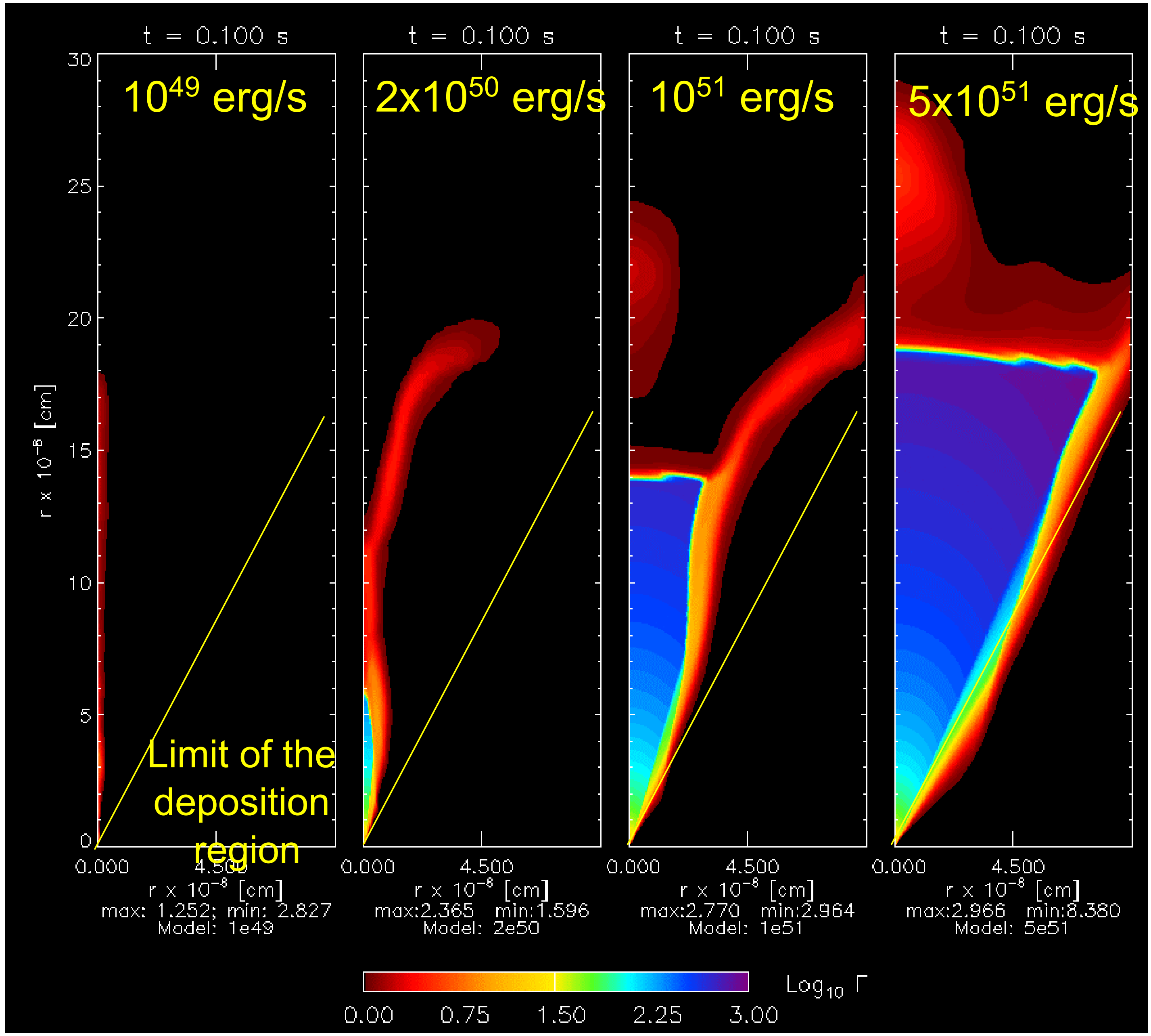
- All the successful models produce relativistic *collimated* outflows:

⇒ initially the disk provides the collimation via cocoon/disk interaction, i.e., the opening angle of the beam is set by the torus inclination.
   - pure hydrodynamic collimation (no need for B- fields).

* For low dE/dt ⇒ jet injection conditions are set after ~ 0.5-1 ms (torus crossing time) with $\square_b$ ~ 3-5.

Results

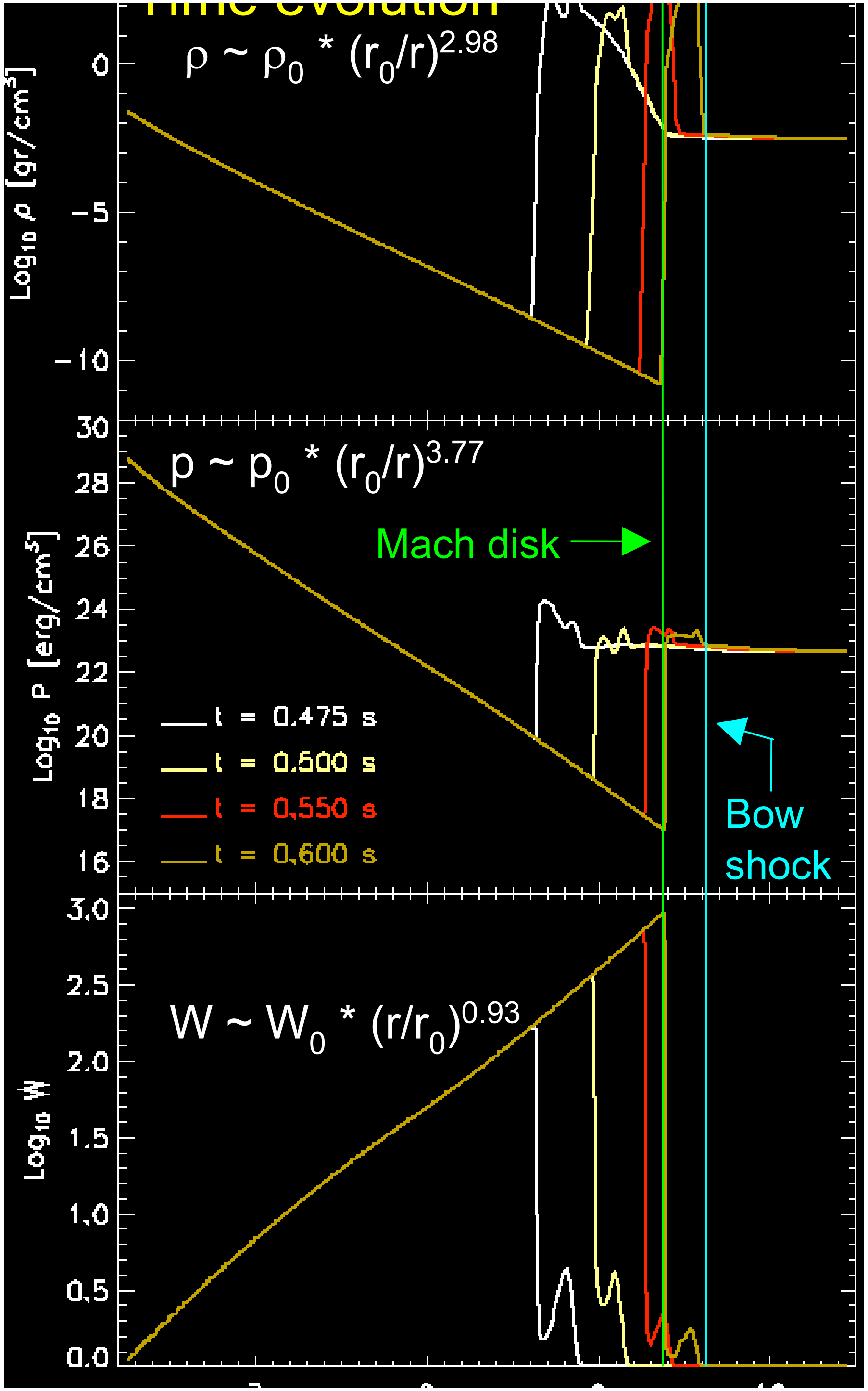
Type A



Morphology: For P> P_{thr} ~ 10^{49} erg/s the outflows are either knotty, narrow, relativistic jets (P < 10^{51} erg/s) or conical, smooth, wide angle, ultrarelativistic winds (P > 10^{51} erg/s).

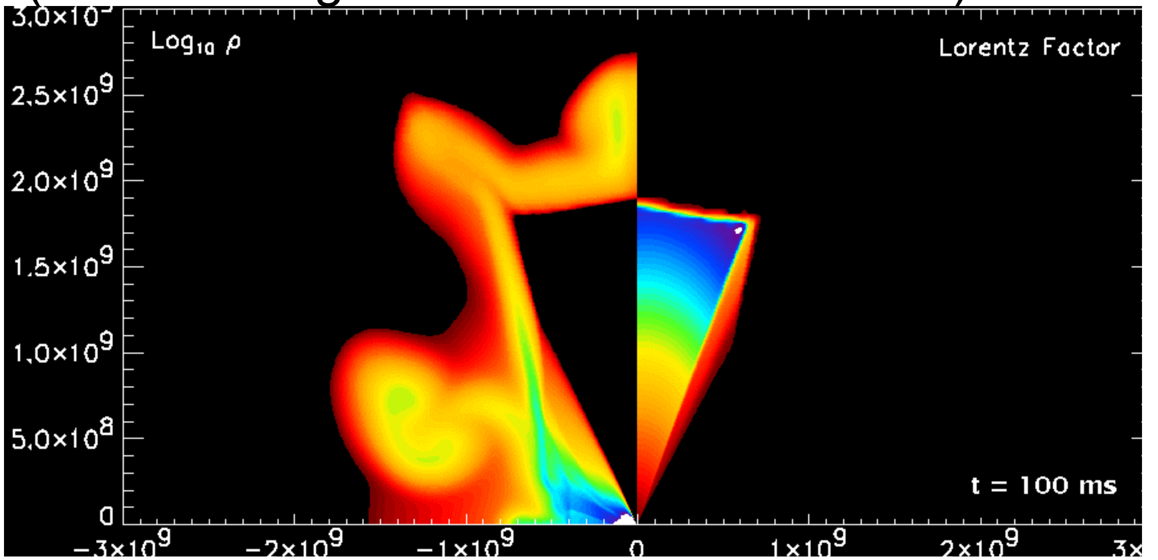
Outflow open. half-angle: It is determined by the high density external medium (low P) or by the inclination angle of the side walls of the torus (large P).

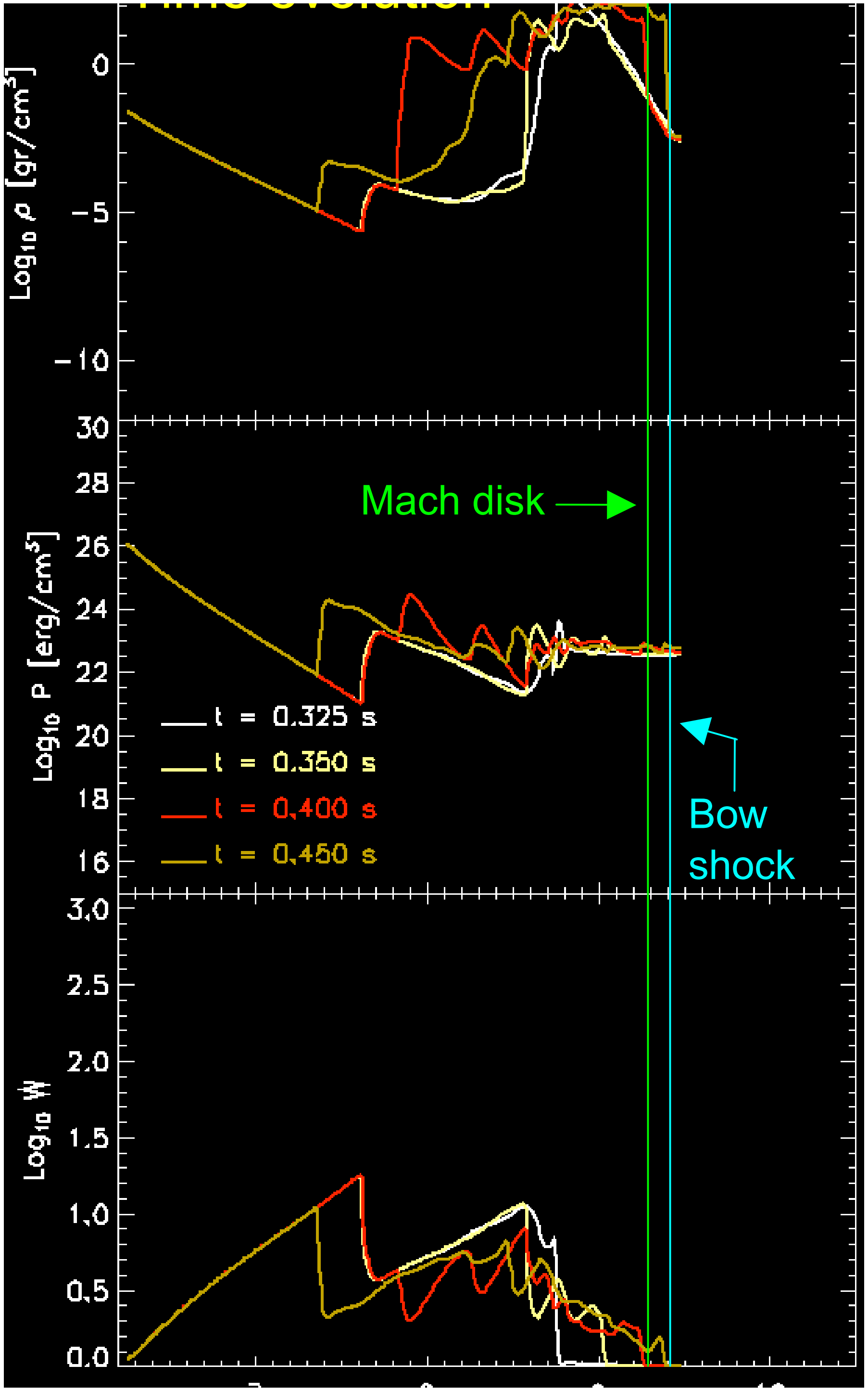
Propagation speed: between ~ 0.6c (P < 10^{51} erg/s) and ~0.97c (P > 10^{51} erg/s)



opening angle ~ 26^0; beaming angle ~ 1/□ ~ 0.1^0

* The *beam* itself has a length ~ 65% of the jet.
  - The distance from the Mach disc to the bow shock grows almost selfsimilarly.
* No internal structure:
  - consequence of the constant high dE/dt (but it doesn't happen for low dE/dt!)
  - correspond to a relativistic conical wind with adiabatic index ~ 1.6 (Levinson & Eichler 2000).
* After 150 ms there is no sign of □ saturation (□ increasing while the source is active)



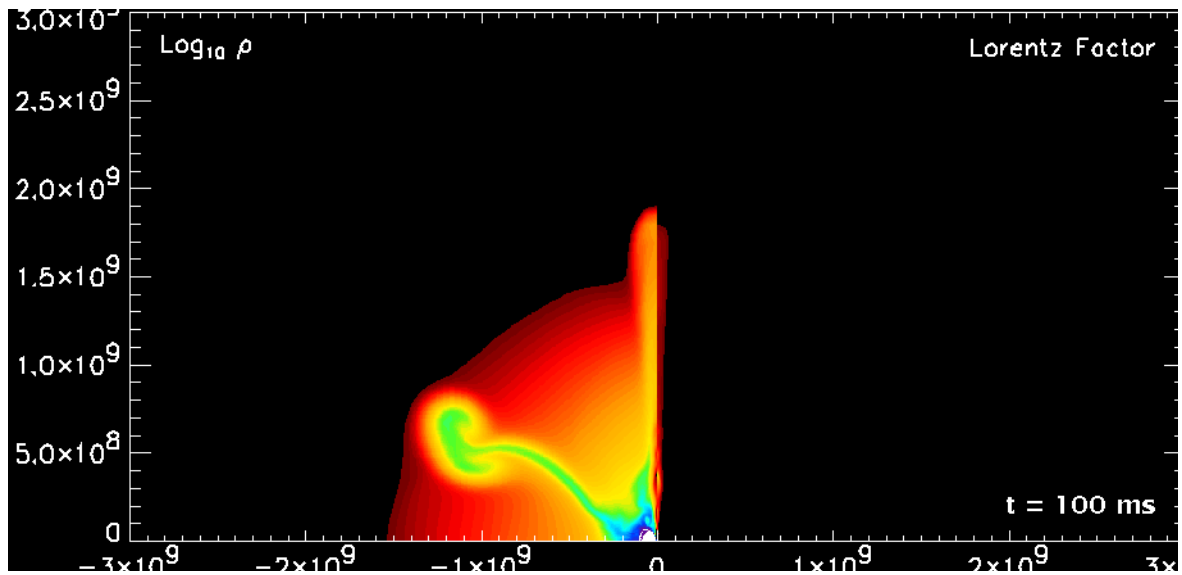


opening angle ~ 2^0 ; beaming angle ~ 1/□ ~ 5^0

* The beam has a length ~90% of the jet.
  - The distance from the Mach disc to the bow shock grows almost self-similarly.

* A lot of internal structure (knotty jet):
  - consequence of the P close to the threshold but also due to KH-instabilities
  - the final outcome won't be a short GRB, observational signature?

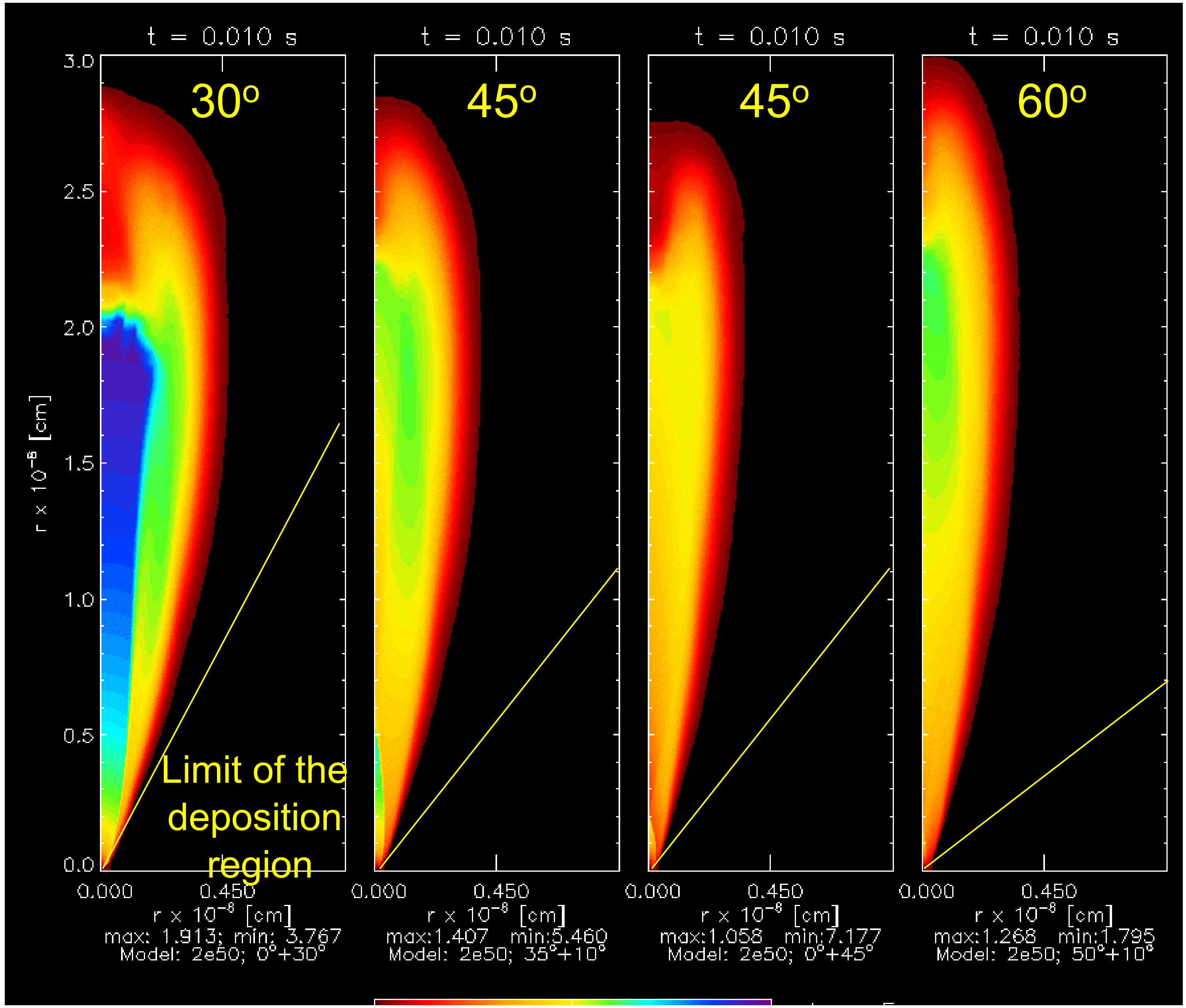
* After 150 ms there □ saturates ~ 15



Results

Type A. Dependence with $\square_0$: Increasing $\square_0$ while keeping $P=2\times10^{50}$ erg/s:

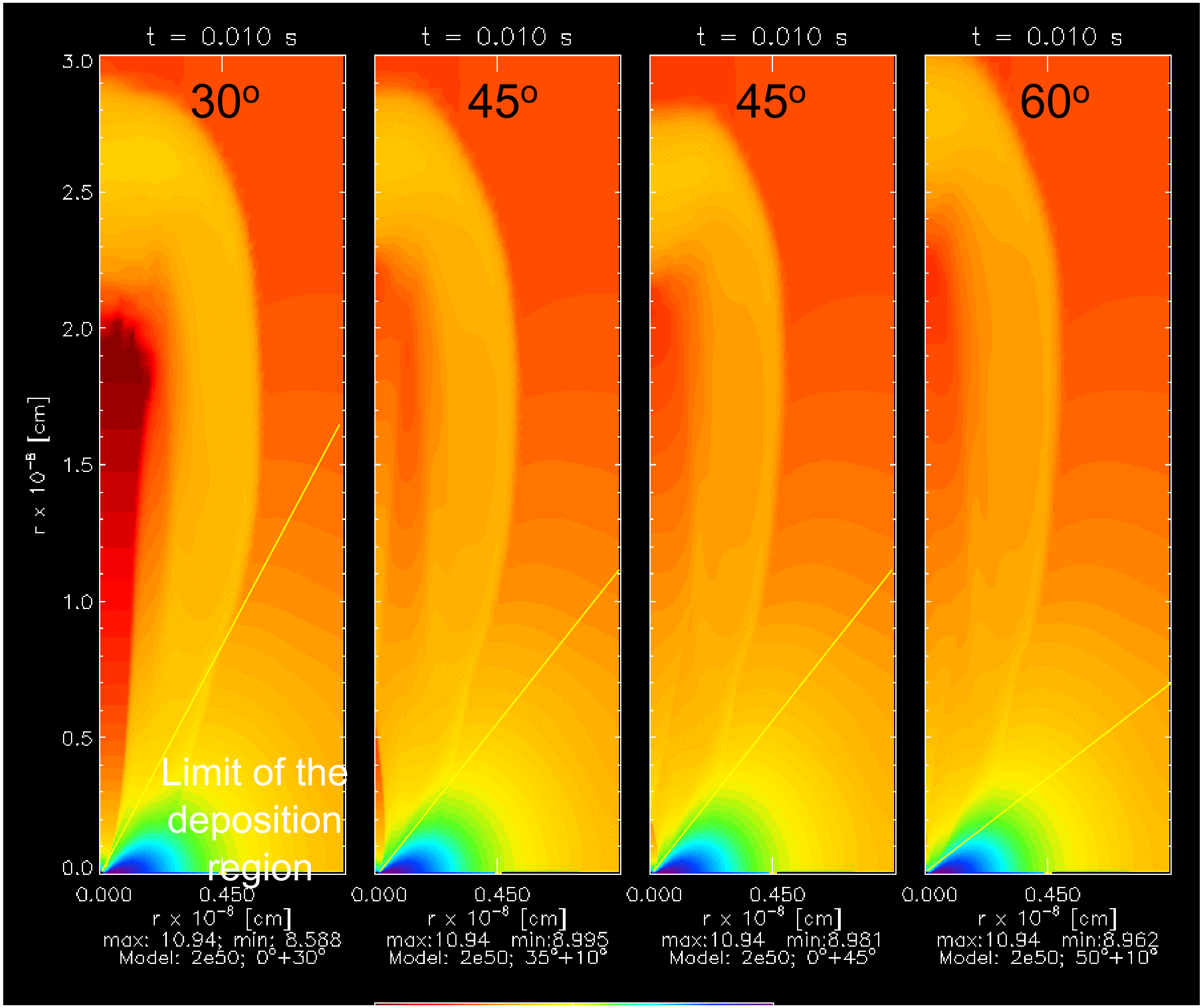
1.- less energy density ⇒ transition from smooth wind to knotty jet (even at early times).



Results

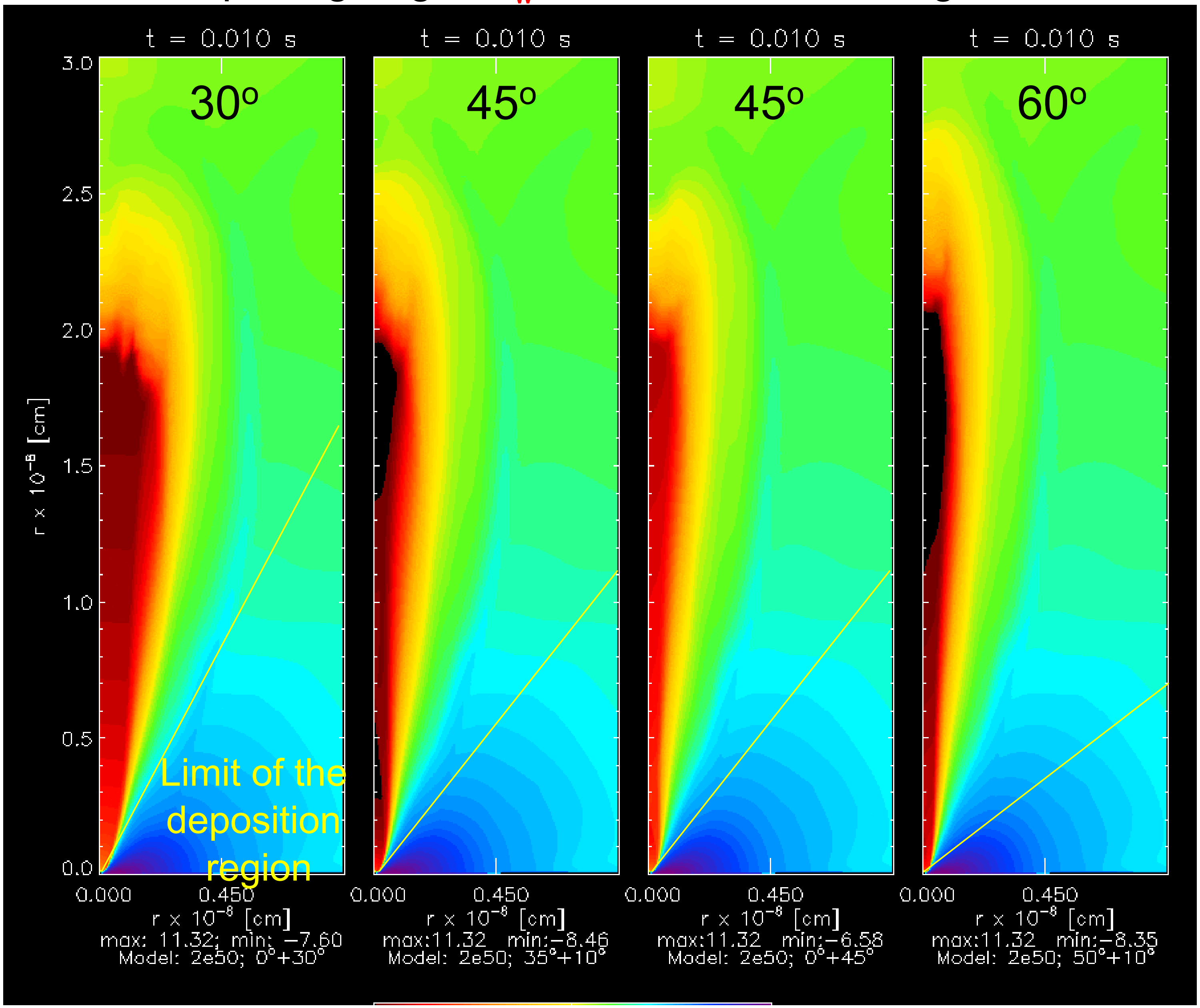
Type A. Dependence with □$_0$: Increasing □$_0$ while keeping $P=2x10^{50}$ erg/s:

2.- larger torus overlap of the deposition region ⇒ increase of T and e.



Type A. Dependence with □$_0$: Increasing □$_0$ while keeping P=2x10^{50} erg/s:

3.- similar flow opening angle □$_w$ ~ 10^o -13^o < torus angle



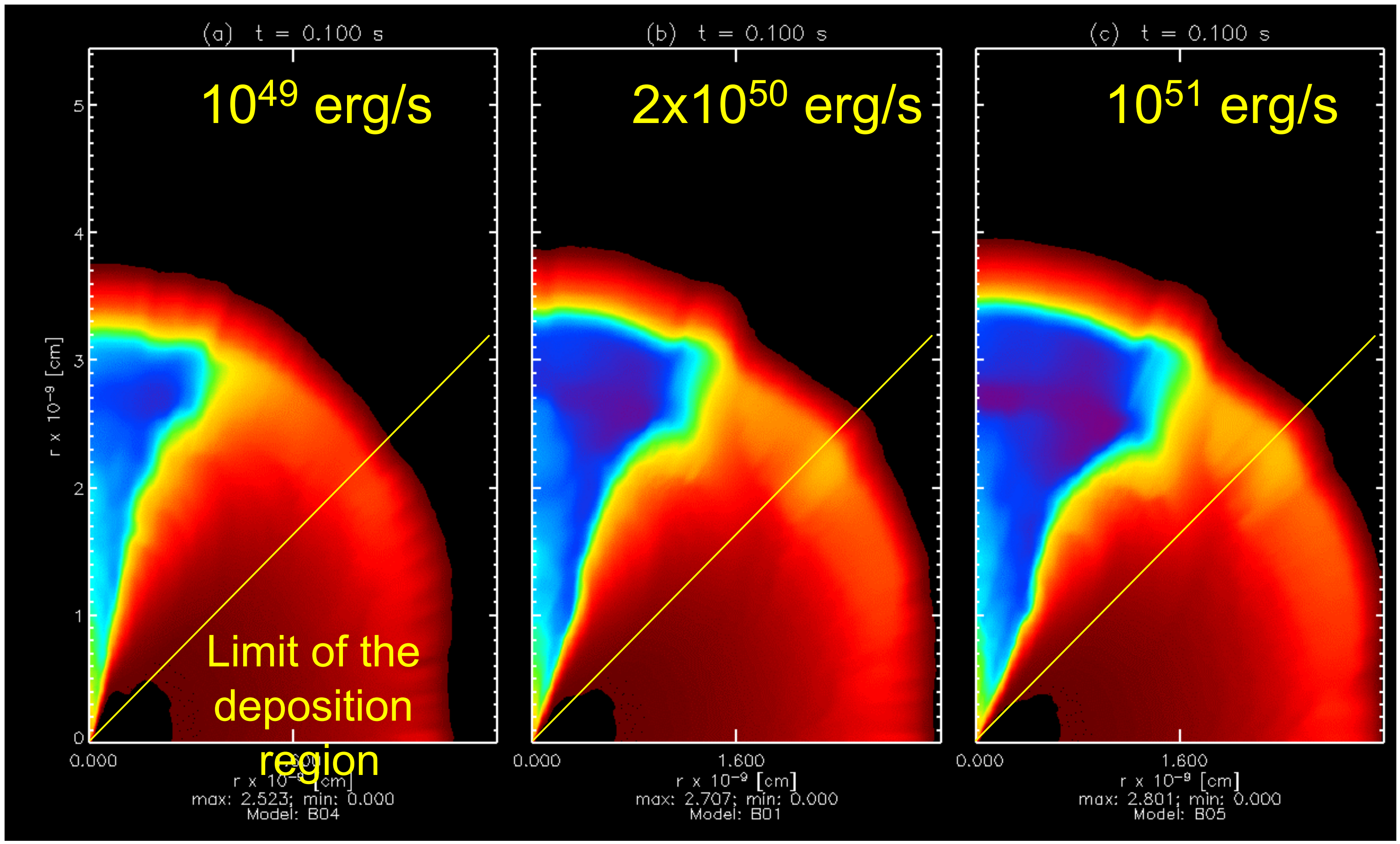
Results

Type B

Morphology: For P> P_{thr} ~ 10^{48} erg/s the outflows are always conical, wide angle, ultrarelativistic jets.

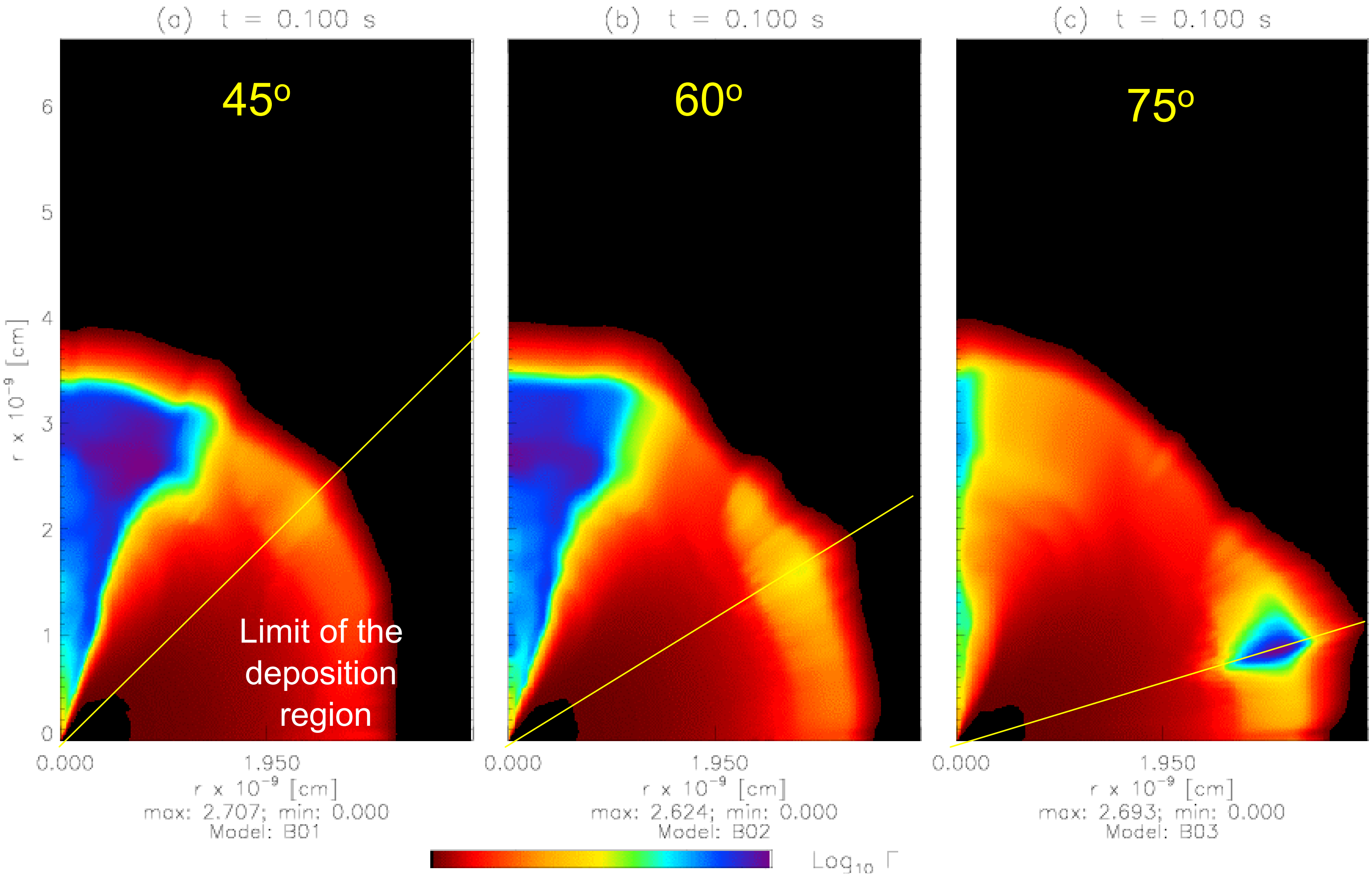
Outflow opening half-angle: ~ 20^o to 25^o. It is determined by the inclination angle of the side walls of the torus (large P).

Propagation speed:
larger than ~0.9999c



Type B. Dependence with $\square_0$: Increasing $\square_0$ while keeping $P=2x10^{50}$ erg/s:

1.- less energy density ⇒ transition from non-smooth wind to knotty jet.

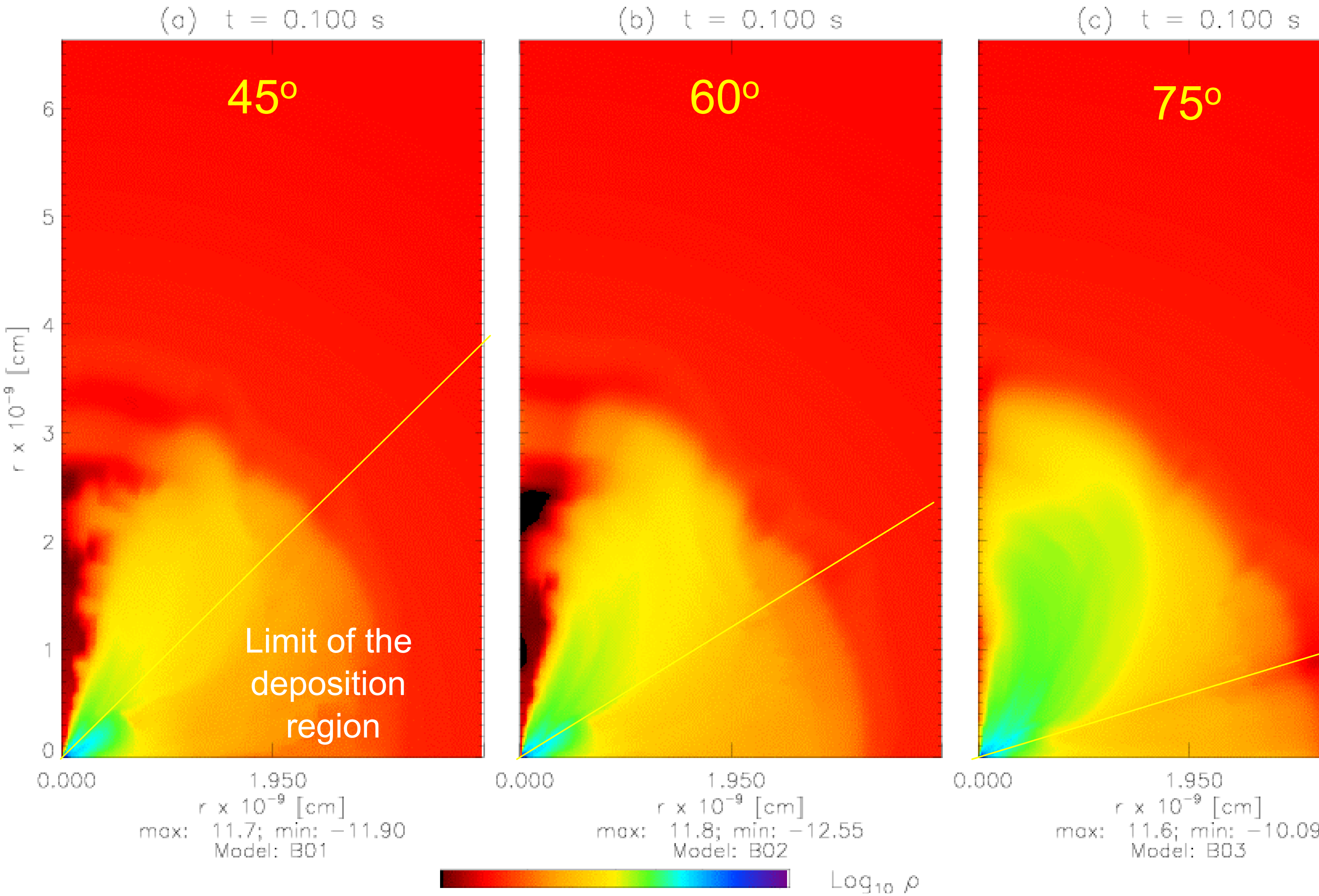


Results

Type B. Dependence with □$_0$: Increasing □$_0$ while keeping P=2x10^{50} erg/s:

1.- less energy density ⇒ transition from non-smooth wind to knotty jet.

2.- larger torus overlap of the deposition region ⇒ increase of density and T.



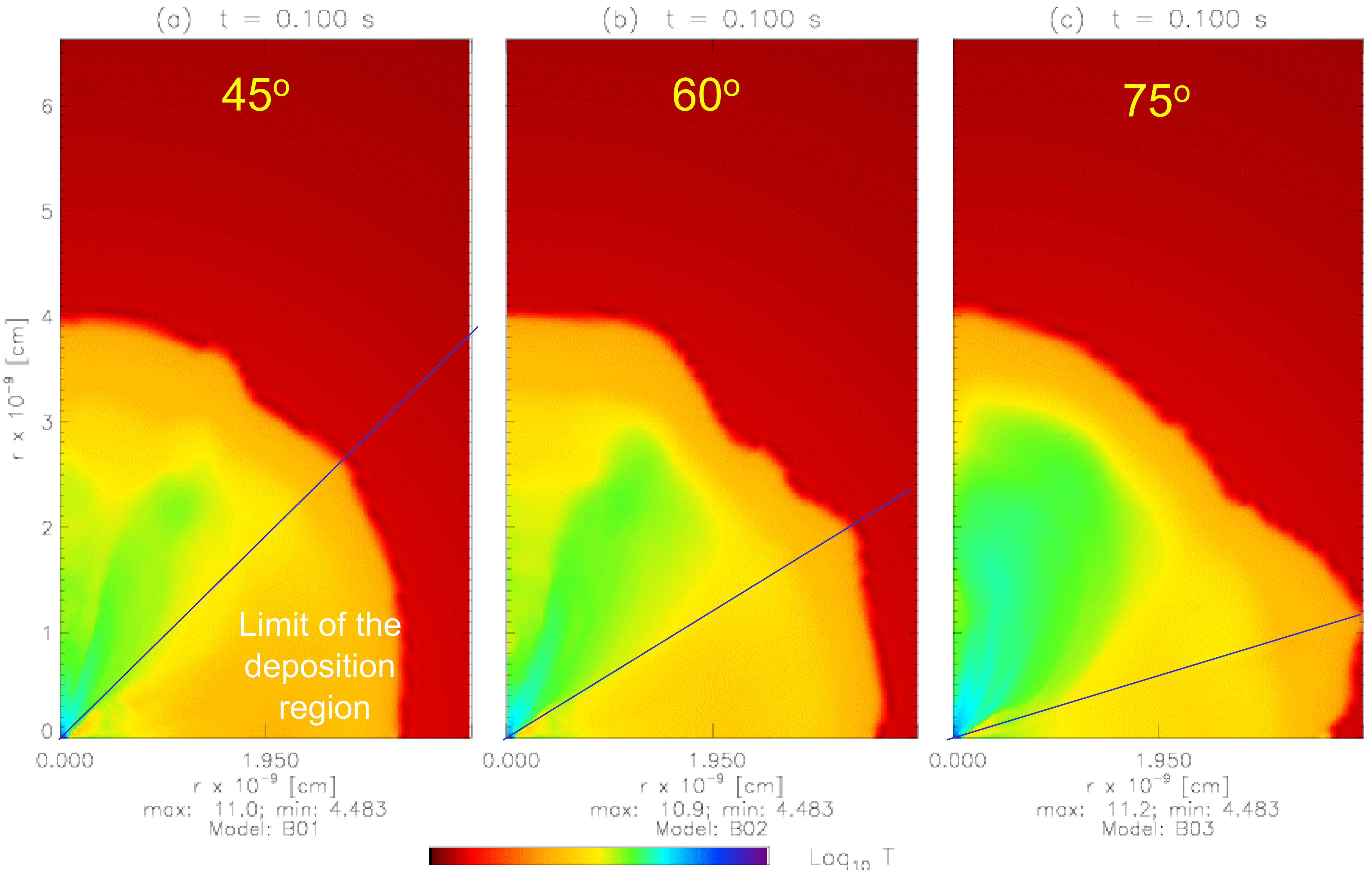
Results

Type B. Dependence with $\square_0$: Increasing $\square_0$ while keeping $P=2\times10^{50}$ erg/s:

1.- less energy density ⇒ transition from non-smooth wind to knotty jet.

2.- larger torus overlap of the deposition region ⇒ increase of density and T.

3.- larger asymmetry of the bubble ⇒ equatorial outflow!



Post switch off evolution

The typical time scale in which the merging of SCBs may release energy is of some fractions of a second.

We have swiched off the energy deposition after T_a=0.1s and followed the subsequent evolution of two models: one of type-A (P =5x10^{51} erg/s in $\square_0$=30^o) and another of type-B (P =2x10^{50} erg/s in $\square_0$=45^o).

A condition to produce a successful GRB is: $V_{rear} \leq V_{front}$ (a)

Type A

Unsuccessful GRB: Condition (a) does not hold because the environment is too dense and the front shock of the fireball decelerates.

Type B

May produce a successful GRB: Condition (a) is $V_{rear} < V_{front}$ in this case. Thus, the fireball stretches radially and, it can produce events with durations of several seconds, i.e., $T_a \ll \square T_{obs}$.

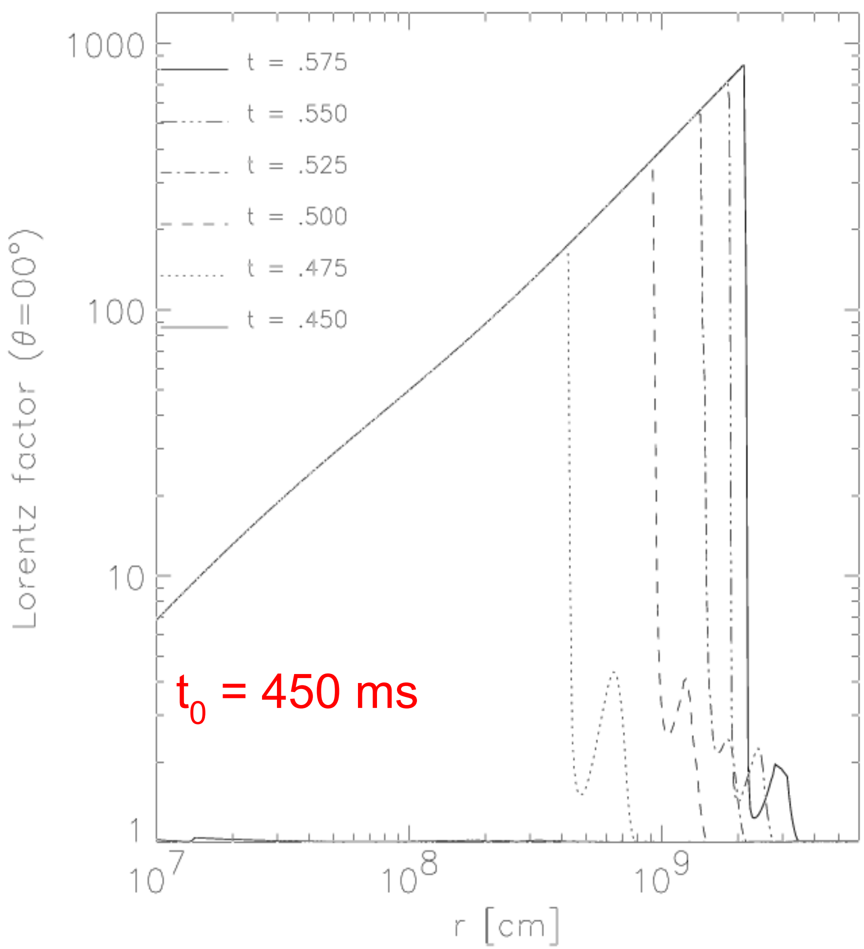
Post-switch-off evolution: Type-A

- For dE/dt = $5x10^{51}$ erg/s the Lorentz factor grows up to ~ 1000 in 100 ms.

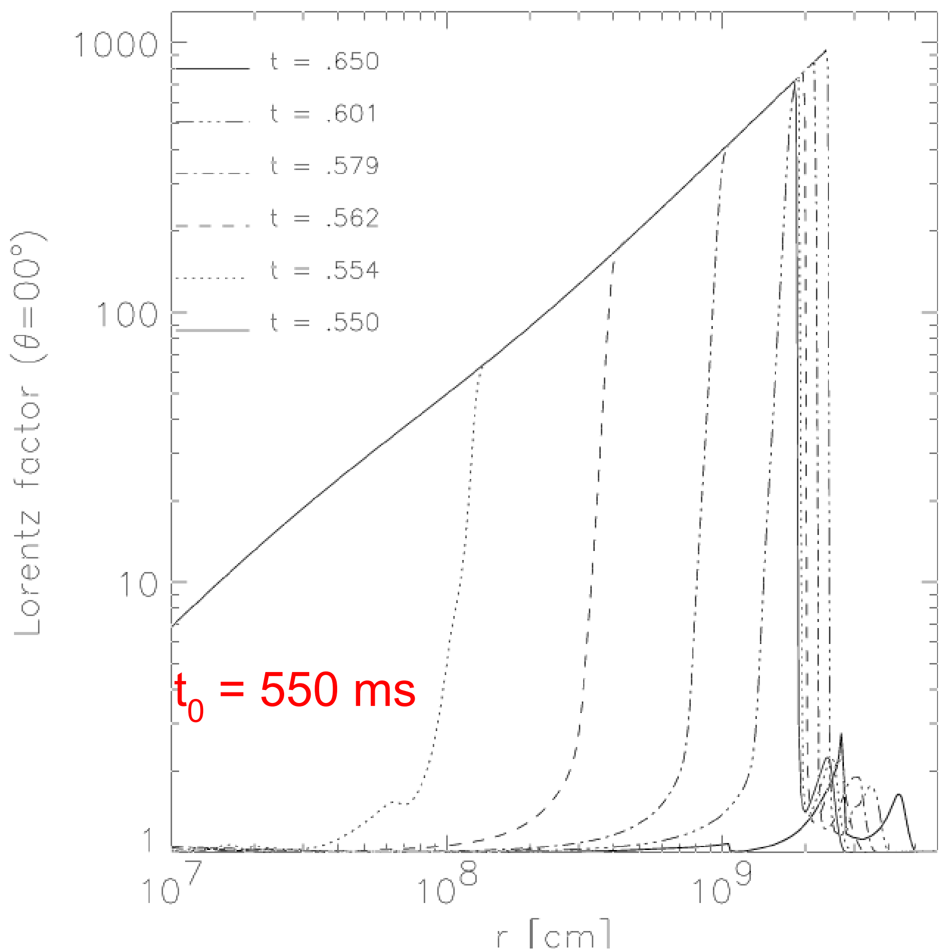
BUT:

- Switching off the energy release after 100 ms leads to an unsuccessful GRB!.

P = $5x10^{51}$erg/s



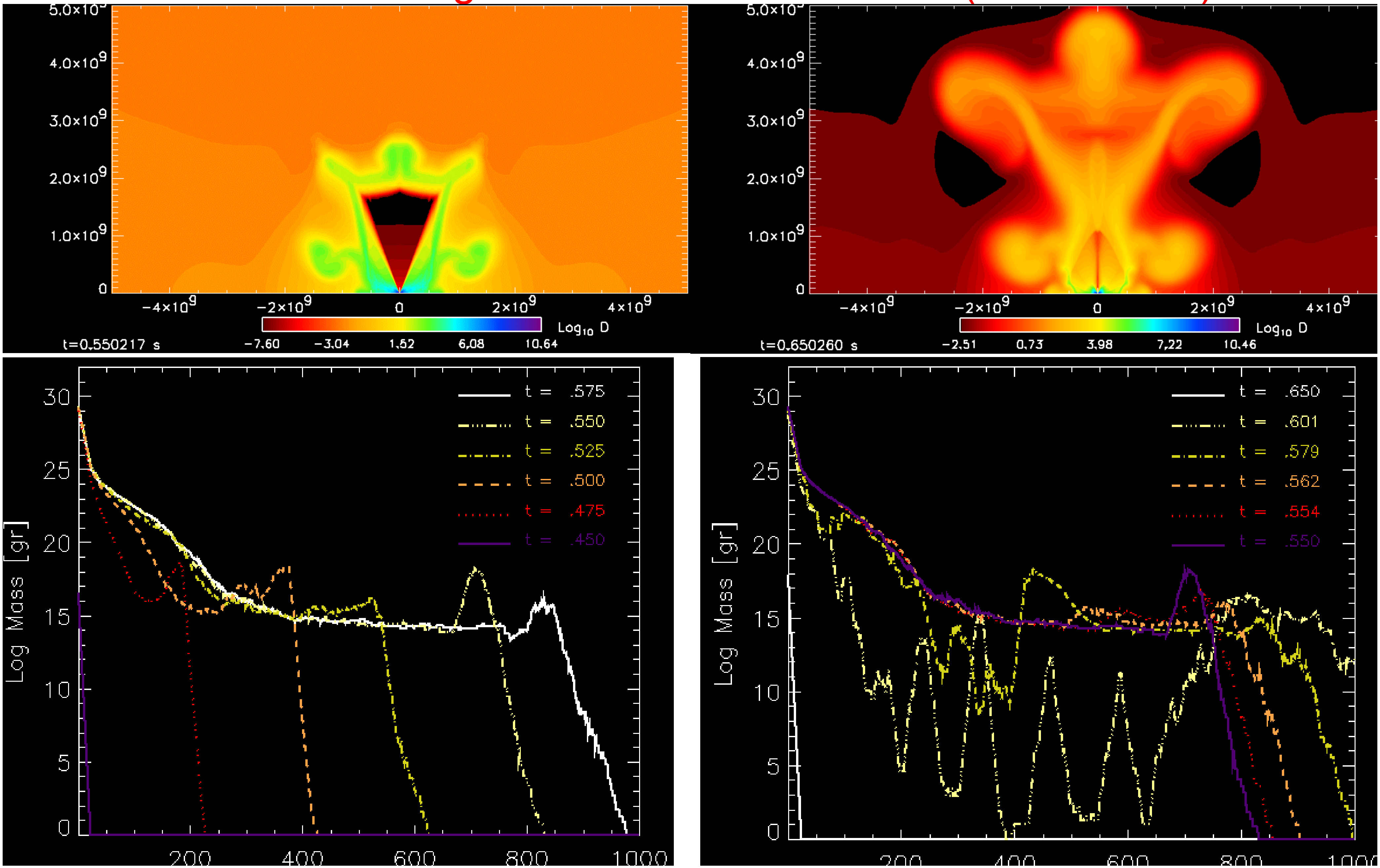
P = 0 (switched off)



Post-switch-on evolution: Type-A

P = 5×10^{51} erg/s

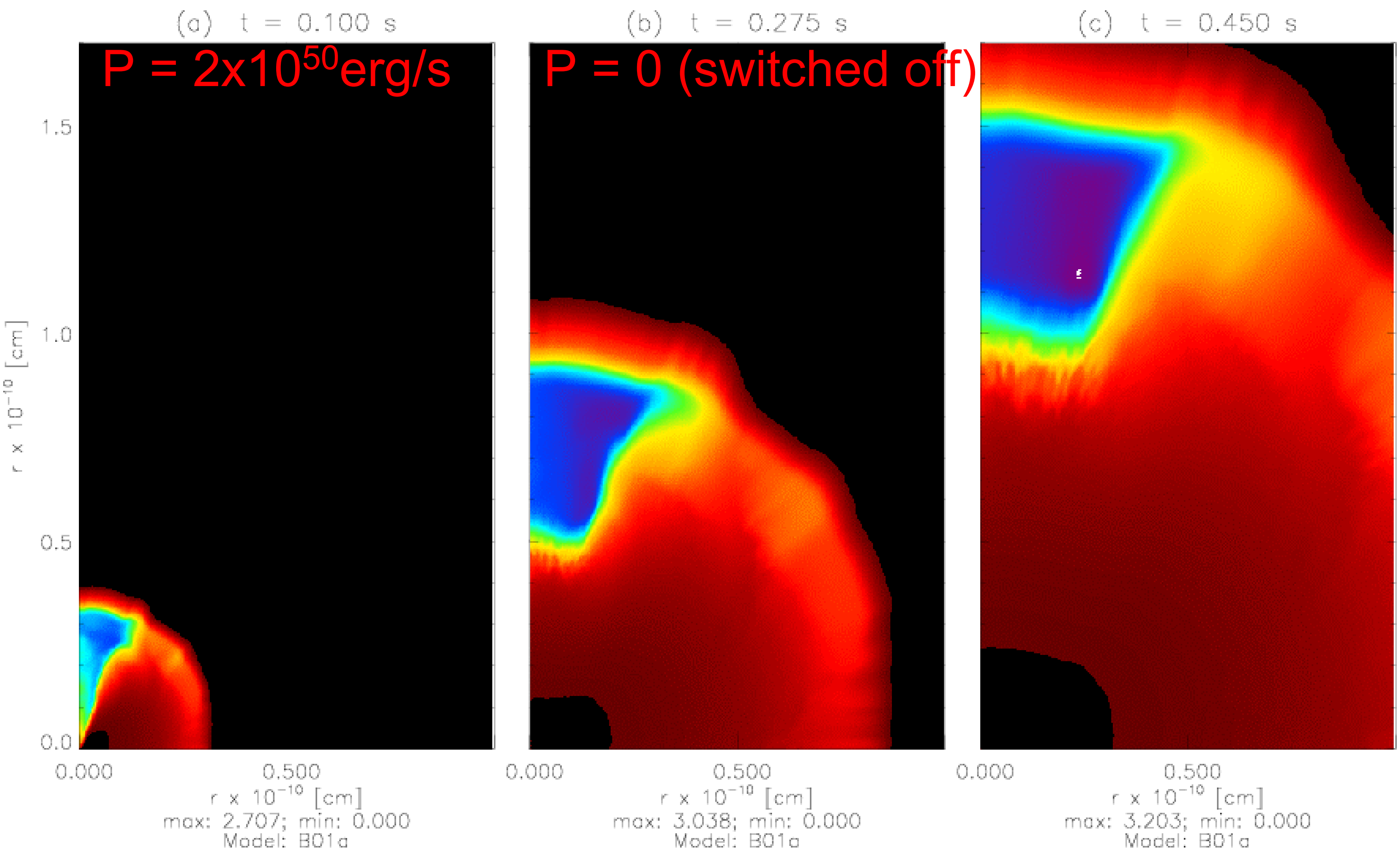
P = 0 (switched off)



Post-switch-off evolution: Type-B

- For P = 2×10^{50} erg/s the Lorentz factor grows up to ~ 1000 in 100 ms.
- Switching off the energy release leads to an almost selfsimilar growth

  ⇒ it is possible to produce a successful GRB!.

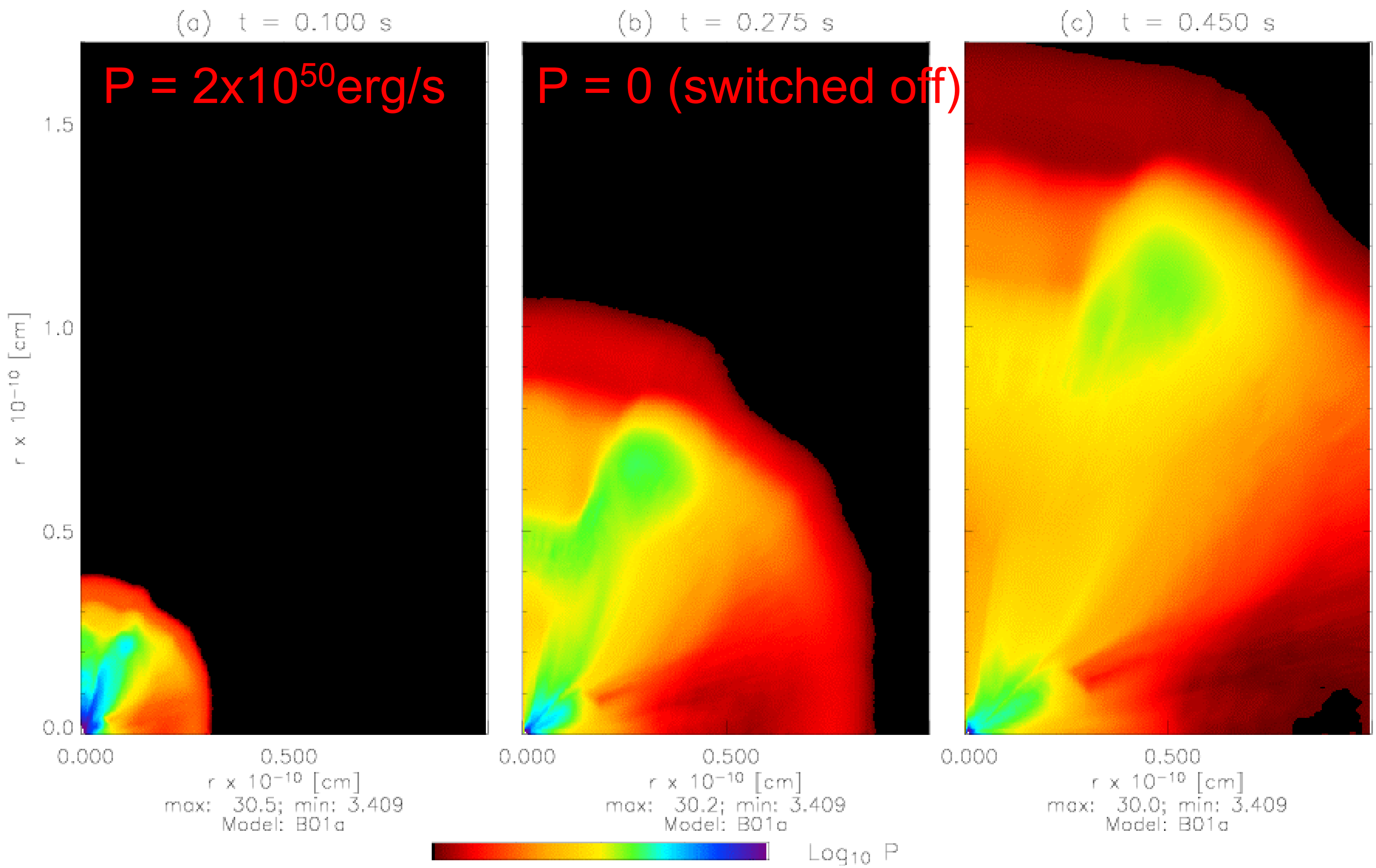


Post-switch-off evolution: Type-B

The fireball has a large internal energy reservoir even after $4.5T_a$

⇒ there is still room for further acceleration

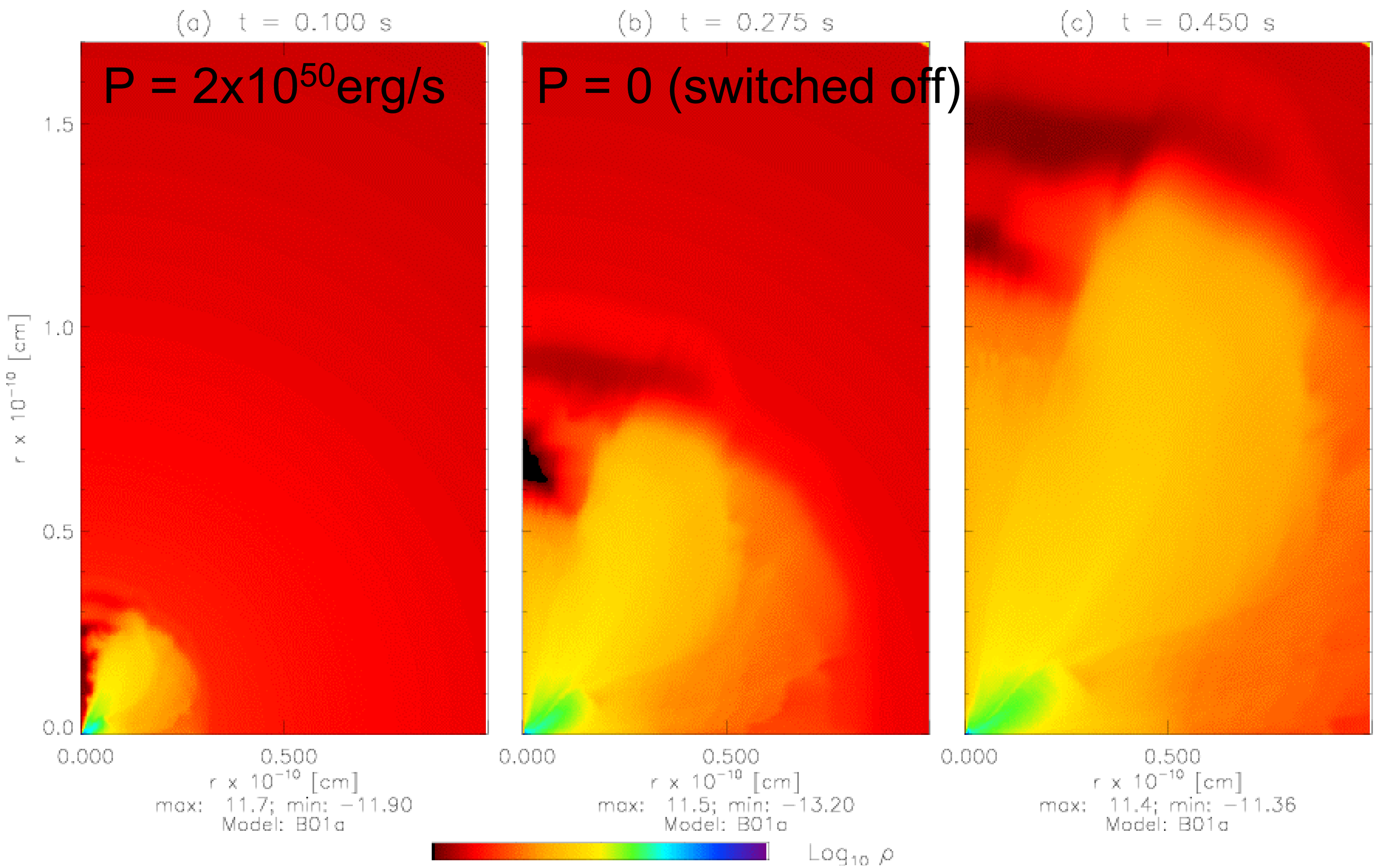
⇒ no sign of saturation



Post-switch-off evolution: Type-B

The density structure is highly irregular

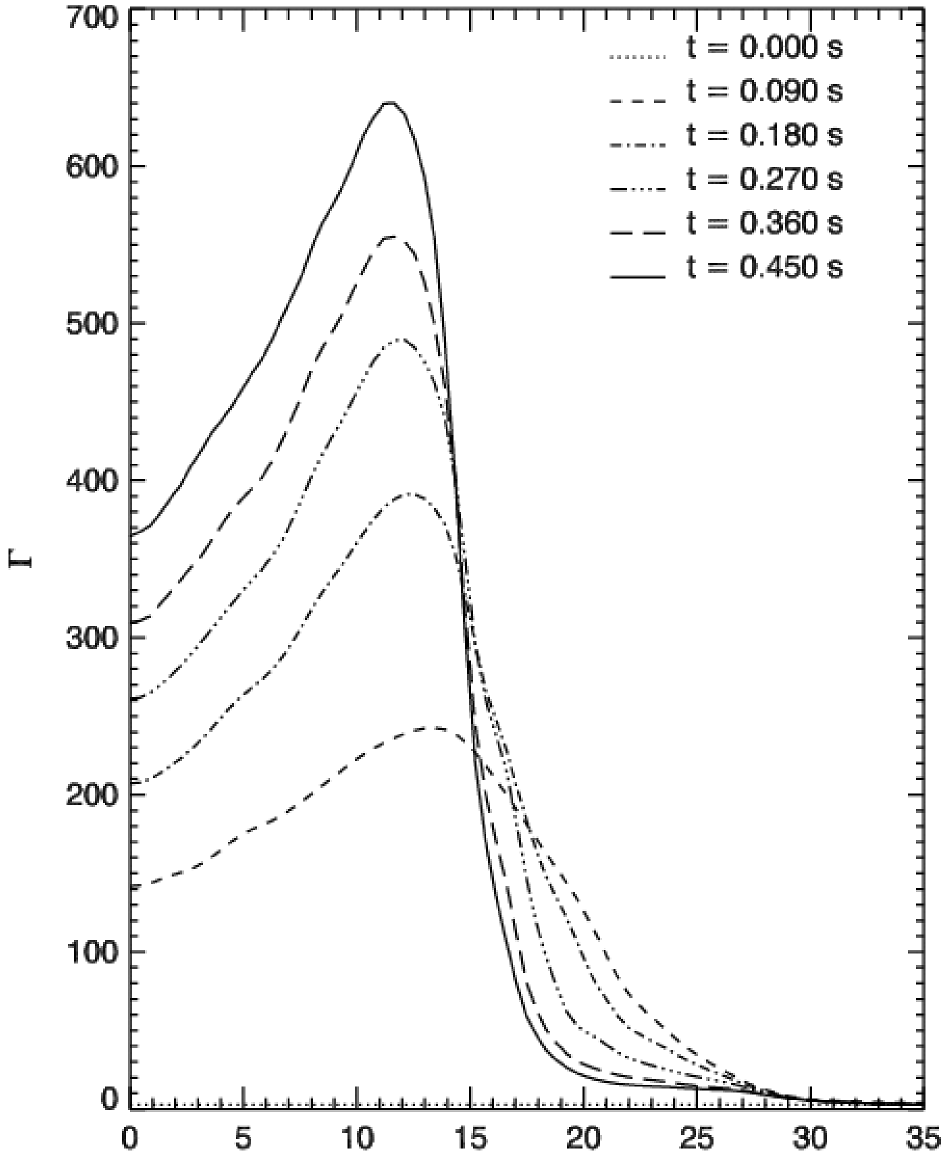
⇒ internal shock develope although the resolution at R>10^{10} cm is not good enough and a part of the structure created is erased.

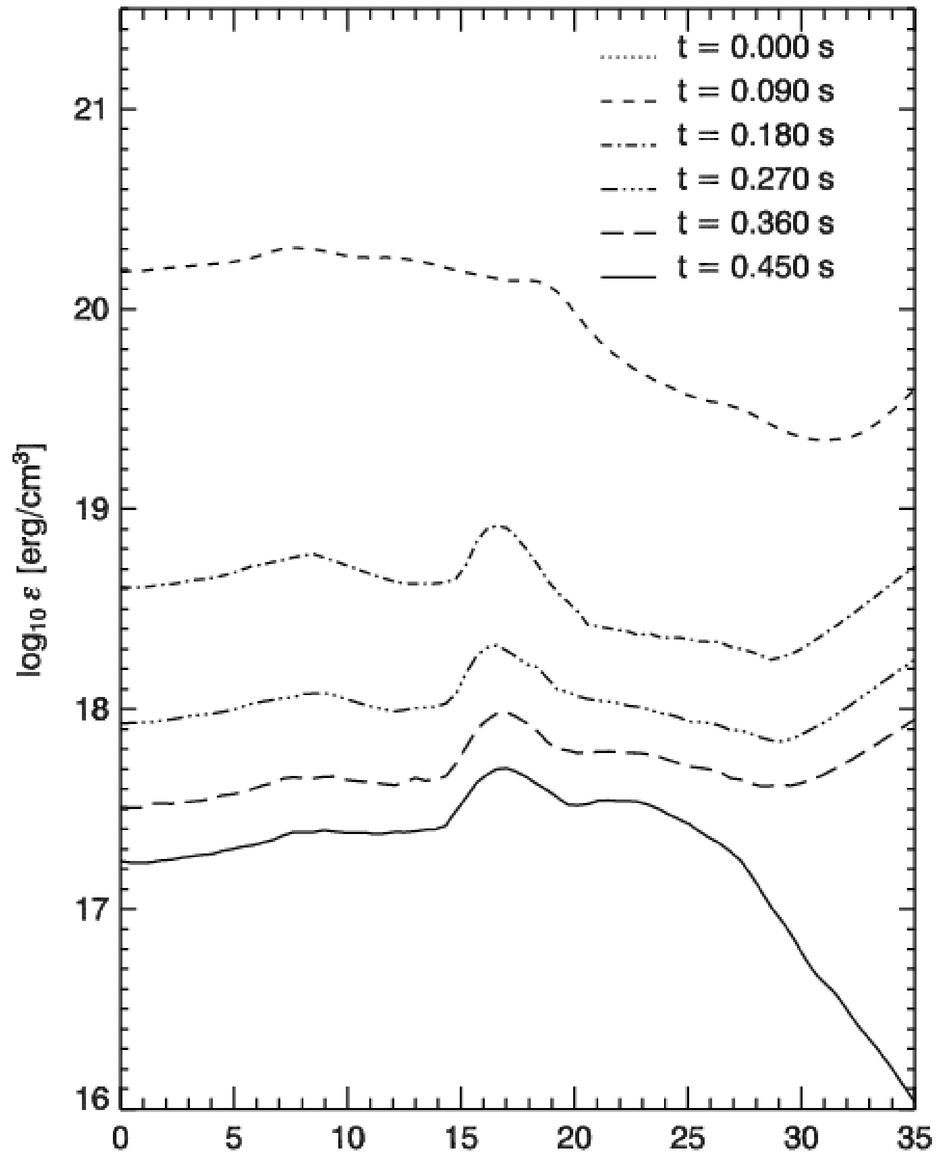


Post-switch-off evolution: Type-B

⇒ The radially averaged variables display a *non-monotonic* shape as a function of □.

⇒ The internal energy as a function of the solid angle is *not constant*.

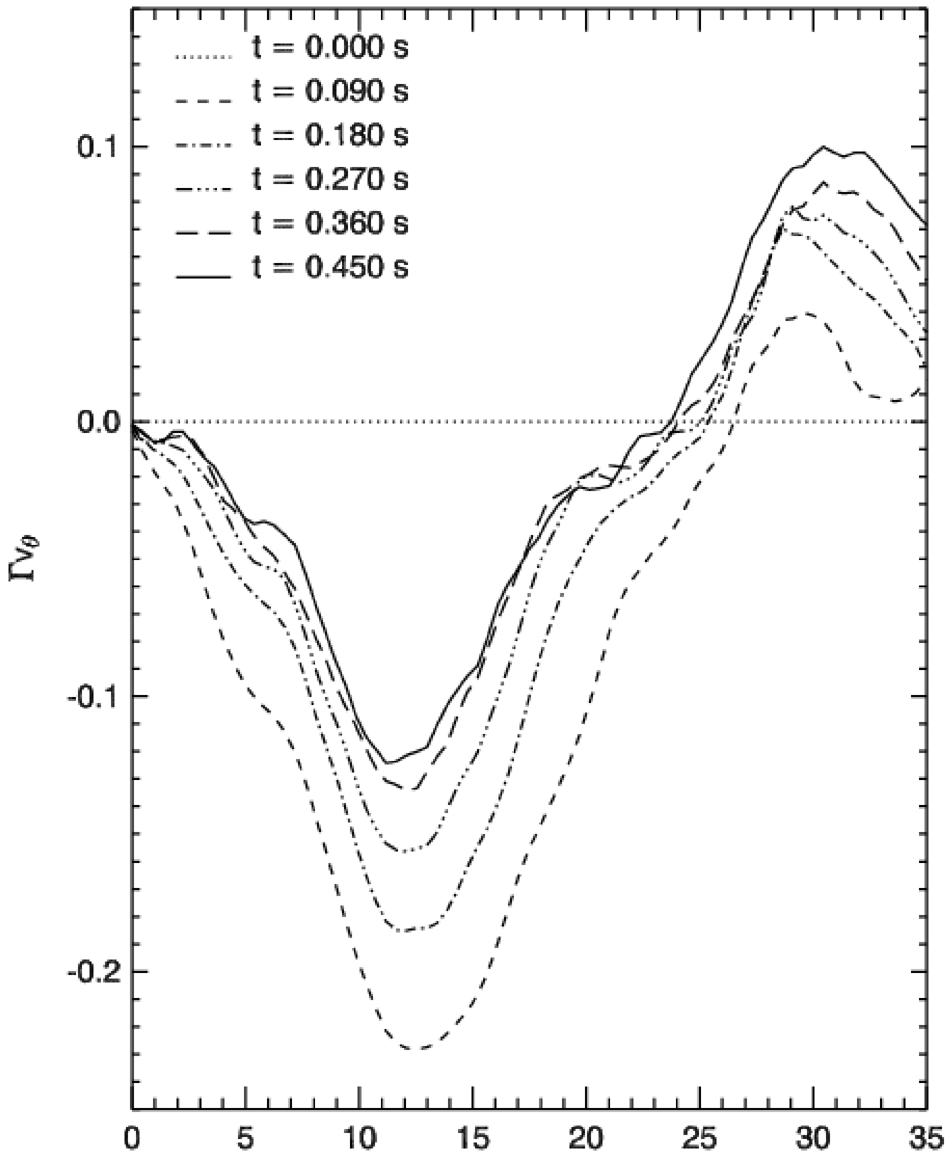


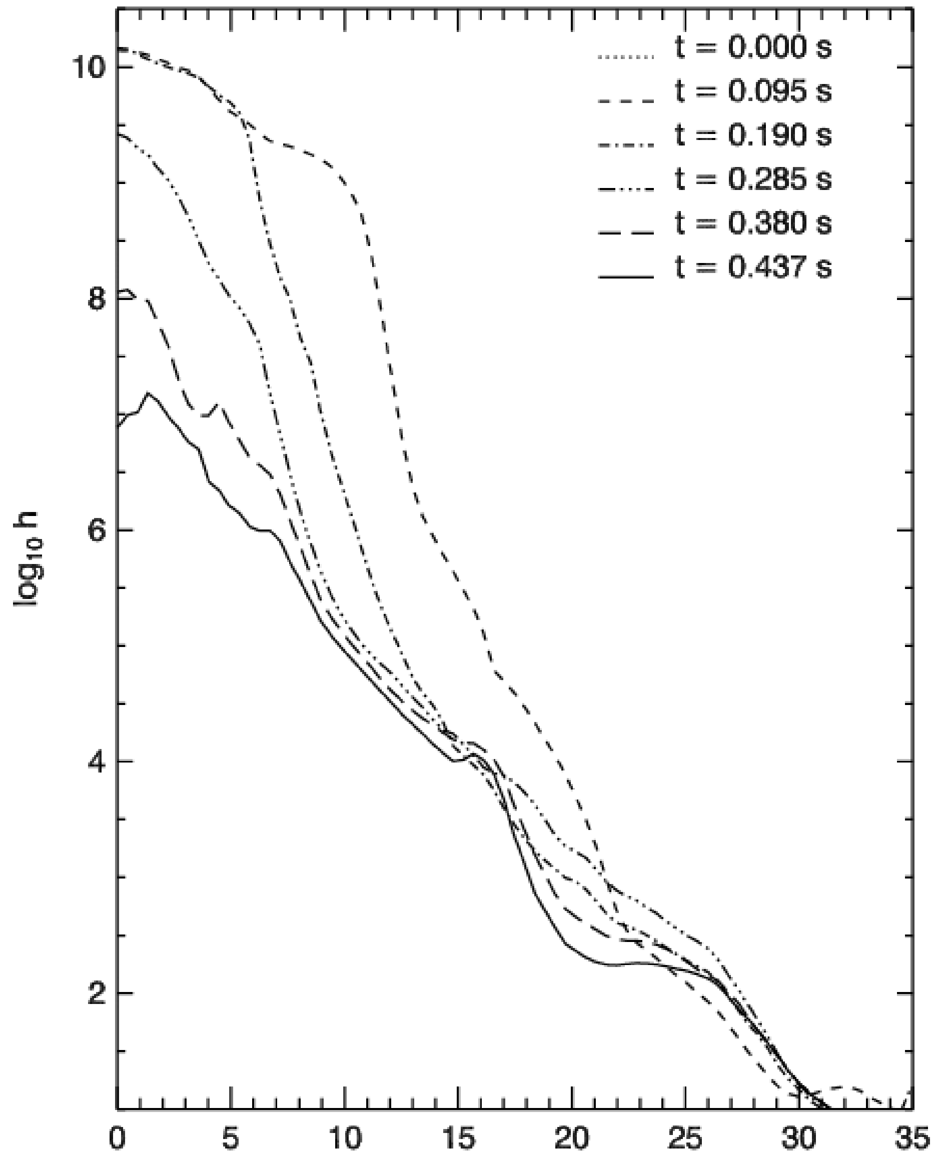


Post-switch-on evolution: Type-B

⇒ The sideways expansion in the comoving frame is subsonic

⇒ A part of the fireball is *contracting!*.





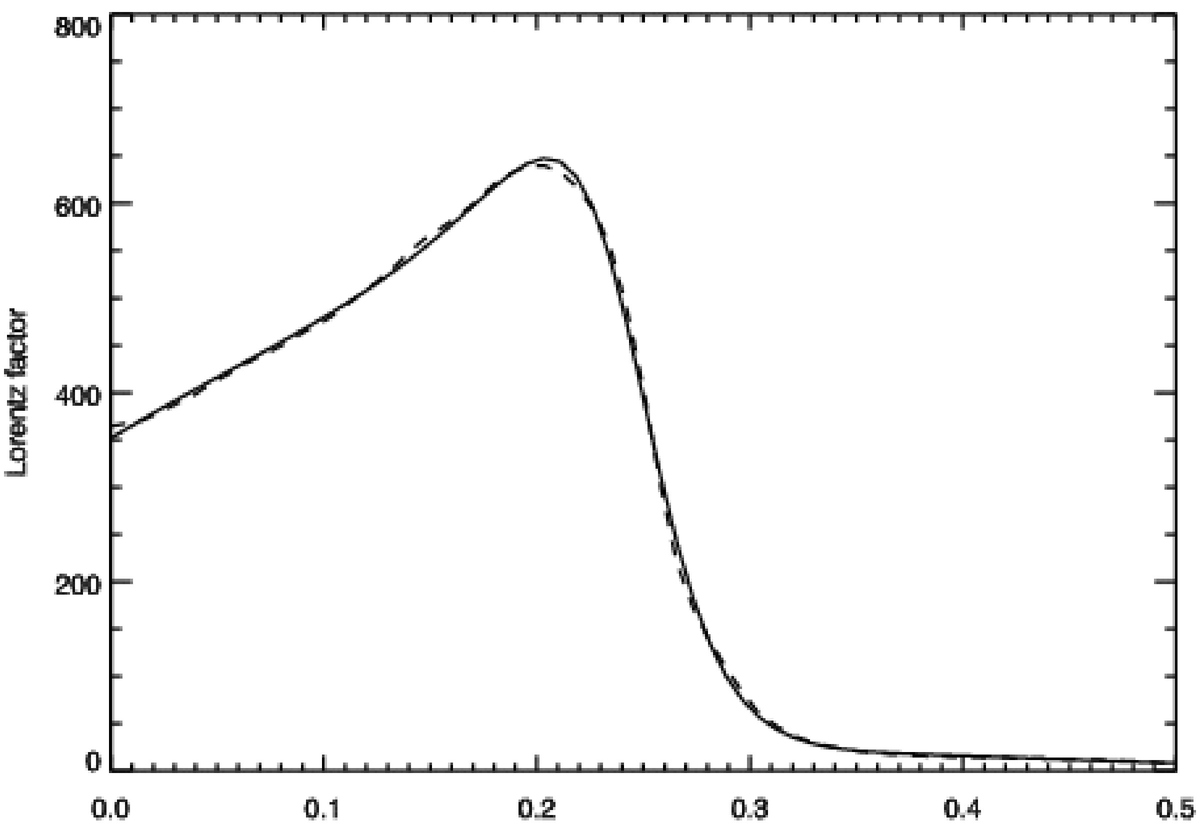
Radially averaged profiles

The fireball structure is inhomogeneous both in radial and angular directions

$\Rightarrow$ disagreement (up to now) with both *Universal* or *Uniform* models.

Universal jet model:

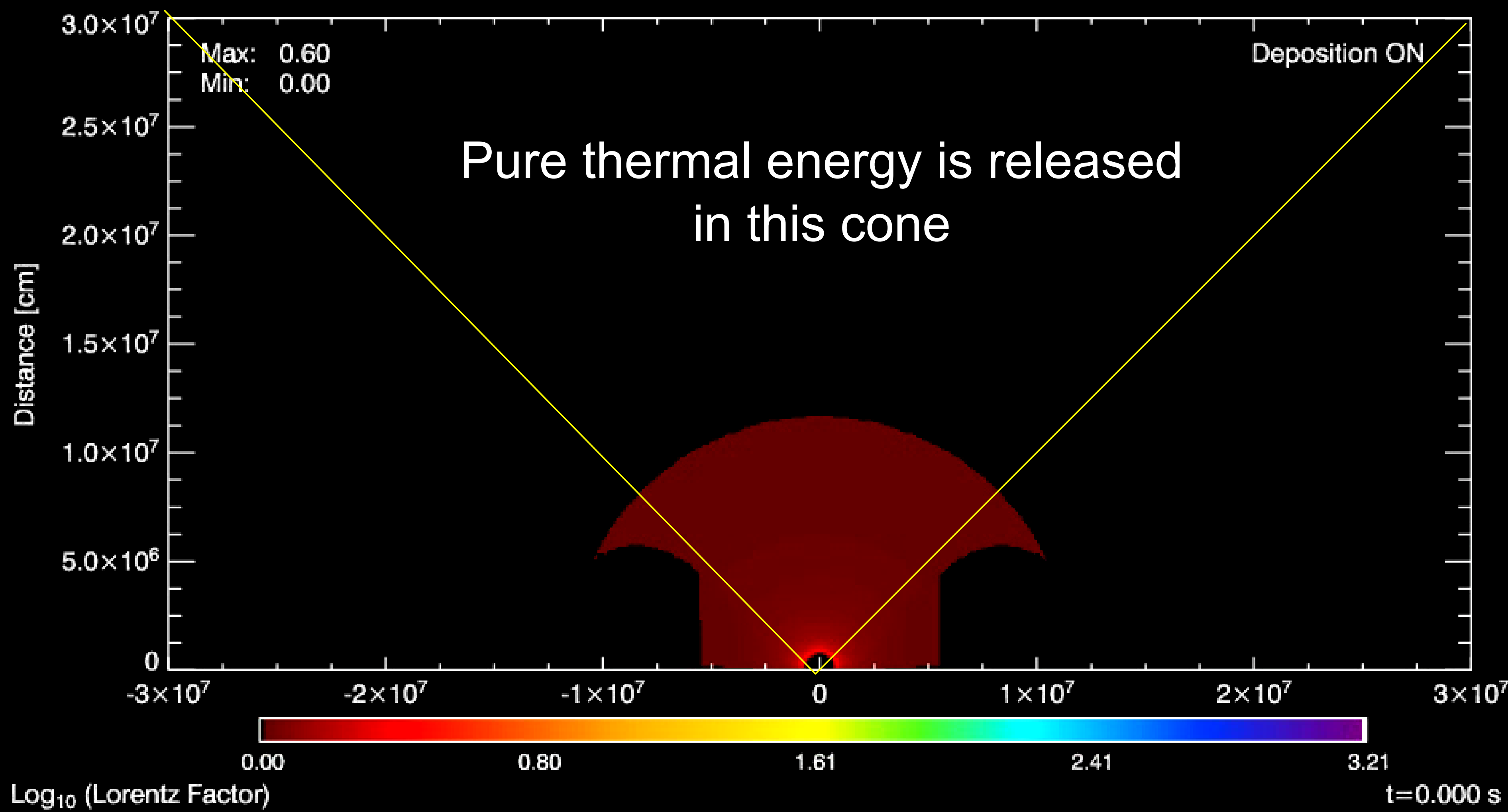
$$\epsilon(\theta,\, t_0) = \epsilon_0 \Theta^{-a}, \quad \Gamma(\theta,\, t_0) = 1 + (\Gamma_0 - 1)\Theta^{-b}\,, \qquad \Theta \equiv \sqrt{1 + \left(\frac{\theta}{\theta_c}\right)^2} \approx \begin{cases} 1, & \text{for } \theta \ll \theta_c, \\ \theta/\theta_c, & \text{for } \theta \gg \theta_c. \end{cases}$$



Best model fit to the Lorentz factor

$$\bar{\Gamma} = 1 + \frac{a_0 + a_1 x + a_2 x^2 + a_3 x^3}{a_4 + a_5 x + \exp(a_6 x)}$$

Likely *first steps* in the life of short GRB
(from t=0 to t=0.460 s)



Model B01:
$P = 2 \times 10^{50}$ erg/s

Concluding remarks:

Releasing energy above the poles at rates and with a functional depencence suggested by Janka et al (1999) relativistic, collimated outflows are produced.

Above our P_{thr}, we generate conical baryon poor winds (BPW) whose opening angle depend on a complex interaction between the fireballs and the walls of the torus and/or the density of the external medium (type-A).

Fixing the deposition angle and increasing the energy rate produces BPWs, more massive and with higher kinetic energy. Once BPWs are formed, either they follow easy, analytic power laws (type-A) or they are non-smooth and do not fit to any power law (type-B) .

A condition to produce a successful GRB is: $V_{rear} \leq V_{front}$ which doesn't hold in type-A models but becomes $V_{rear} < V_{front}$ in type-B ones.

The fireball stretches radially and, it can produce events with durations of several seconds.

The fireball structure is inhomogeneous both in radial and angular directions

$\Rightarrow$ disagreement (up to now) with both *Universal* or *Uniform* models